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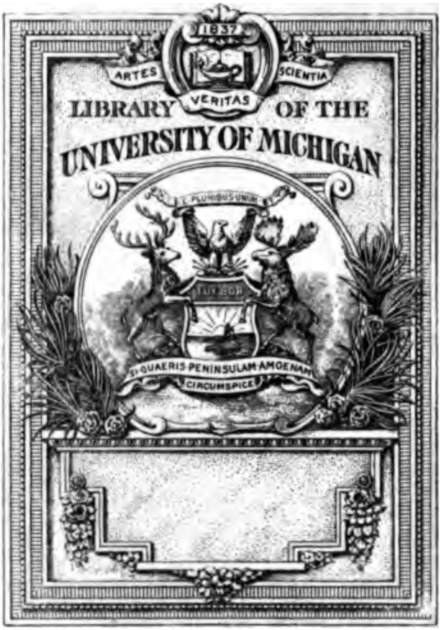
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LECTURES

ON

POLARIZED LIGHT.

LONDON:
A. and G. A. SPOTTISWOODE,
New-street-Square.

345-8

LECTURES
ON
POLARIZED LIGHT,
TOGETHER WITH A LECTURE ON THE
MICROSCOPE,

DELIVERED BEFORE
THE PHARMACEUTICAL SOCIETY OF GREAT BRITAIN, AND AT
THE MEDICAL SCHOOL OF THE LONDON HOSPITAL.

BY THE LATE
JONATHAN PEREIRA, ESQ., M.D. F.R.S. F.L.S.
FELLOW OF THE ROYAL COLLEGE OF PHYSICIANS,
VICE-PRESIDENT OF THE ROYAL MEDICAL AND CHIRURGICAL SOCIETY,
PHYSICIAN TO THE LONDON HOSPITAL, AND MEMBER OF
SEVERAL FOREIGN SOCIETIES.

ILLUSTRATED BY NUMEROUS WOODCUTS.

SECOND EDITION,
GREATLY ENLARGED FROM MATERIALS LEFT BY THE AUTHOR.

EDITED BY THE
REV. BADEN POWELL, M.A. V.P.R.S. &c.
SAVILIAN PROFESSOR OF GEOMETRY IN THE UNIVERSITY OF OXFORD.

LONDON:
LONGMAN, BROWN, GREEN, AND LONGMANS.
1854.

TO

CHARLES WOODWARD, ESQ., F.R.S.,

PRESIDENT OF THE ISLINGTON LITERARY AND

SCIENTIFIC SOCIETY,

This Work,

ON A SUBJECT WITH WHICH HE IS INTIMATELY ACQUAINTED,

IS INSCRIBED,

AS A TESTIMONY OF RESPECT AND ESTEEM,

BY HIS SINCERE FRIEND,

THE AUTHOR.

AUTHOR'S PREFACE

TO

THE FIRST EDITION.

THE following Lectures were delivered in the spring of 1843, before the Members of the PHARMACEUTICAL SOCIETY OF GREAT BRITAIN, and are now in course of publication in the *Pharmaceutical Journal.* The substance of them has formed, for some years past, a portion of the Annual Course on Chemistry, delivered in the MEDICAL SCHOOL of the London Hospital.

To the undermentioned eminent philosophers the author has been principally indebted for the information contained in the following pages:

Sir Isaac Newton. — Opticks; or, a Treatise of the Reflections, Refractions, Inflections, and Colours of Light.

Dr. Thomas Young. — A Course of Lectures on Natural Philosophy and the Mechanical Arts.

Sir D. Brewster.—Various papers in the Transactions of the Royal Societies of London and Edinburgh. Also two numbers on the Double Refraction and Polarization of Light, published under the superintendence of the Society for the Diffusion of Useful Knowledge. Likewise, a Treatise on Optics, in Lardner's Cyclopædia, and the article "Optics" in the Encyclopædia Britannica, 7th edition.

Fresnel.—Elementary View of the Undulatory Theory of Light, in the Quarterly Journal of Science for 1827, 1828, 1829, translated and annotated by Dr. Thomas Young. Also various papers in the Annales de Chimie et de Physique. Likewise, Extrait du Bulletin de la Société Philomatique, Décembre, 1822, and Février, 1823.

Sir J. Herschel.—Article "Light," in the Encyclopædia Metropolitana. Also, Transactions of the Cambridge Philosophical Society, and Philosophical Transactions.

Biot.—Various papers in the Mémoires de l'Académie Royale des Sciences, and in the Annales de Chimie et de Physique.

Airy.—Mathematical Tracts. 2d edit. 1831. Also, Transactions of the Cambridge Philosophical Society.

Pouillet. — Elémens de Physique Expérimentale et de Météorologie, 2 vols. 1827.

Peclet. — Traité Elémentaire de Physique. 2^me ed. 2 vols. 1830.

Quetelet. — Notes to the French Translation of Herschel's Article on Light. Also, Positions de Physique. 1834.

Lloyd, Rev. H. — Report on the Progress and Present State of Physical Optics, in the Report of the Fourth Meeting of the British Association. 1835. Also, Lectures on the Wave Theory of Light. 1841.

Powell, Rev. Professor. — Elementary Treatise on Experimental and Mathematical Optics. 1833. Also, a General and Elementary View of the Undulatory Theory, as applied to the Dispersion of Light. 1841. Likewise, various papers in the Philosophical Magazine and Philosophical Transactions.

Rose, Gustav. — Elemente der Krystallographie. 2^te. Aufl. 1838. (A French translation of the 1st edition of this work.)

Dove. — On the Circular Polarization of Light: translated in Taylor's Scientific Memoirs, vol. i.

Soubeiran. — Journal de Pharmacie. 1842.

Ventzke. — Annals of Chemistry. December, 1842.

The author takes this opportunity of offering his warmest thanks to his friend, Mr. Woodward, for his valuable assistance and advice on many occasions, in the performance of experiments on Polarized Light; as well as for the loan of various pieces of apparatus, contrived and adapted by Mr. Woodward, for the public illustration of the phenomena of Polarized Light.

To Mr. Darker, optician and manufacturer of polarizing apparatus, of Paradise Street, Lambeth, the thanks of the author are also justly due, for his disinterested zeal, skill, and attention in promoting the objects of the author in the preparation of the present course of Lectures.

J. P.

47. Finsbury Square,
September, 1843.

EDITOR'S PREFACE.

In November, 1853, I received a communication from the widow of the late Dr. Pereira, mentioning that a new edition of his Lectures on Polarized Light was called for, and requesting me to undertake the office of Editor, and at the same time informing me that the Author had left numerous notes and additions preparatory to a new edition of his work.

The Publishers having concurred in this proposal, the materials were placed in my hands, with ample discretion as to the use of them, and for making such other alterations or additions as might appear to me calculated to further the proposed object of the work, viz.: to give not an abstruse and scientific discussion of the subject, but the most elementary, popular, and explanatory view possible.

In endeavouring to carry this design into effect, I have felt it proper to deviate as little as possible from the existing form and character of the work. The style adopted by the author is that of familiar explanation adapted to a spoken Lecture rather than to a written work: but I have throughout retained it, as well suited to elementary illustration. In some few parts I have ventured to omit a sentence or paragraph, when it seemed to me of questionable utility; and have in a few places altered modes of expression which appeared likely to lead to ambiguity or error, or to involve conjectural speculations open to doubt. The additions contemplated by the author himself are of considerable extent: they were mostly written in the form of detached fragments, which I have attempted uniformly to incorporate with the text; and often in mere notes or memoranda, which I have moulded into sentences.

As to the arrangement of the subjects, though in some respects not exactly what I should have chosen, yet presuming it to have been the best adapted for the particular objects the author had more immediately in view, I have retained it unchanged, except only in two instances: 1st, the restoration of the Section on "Macled Crystals," to what seemed its more natural position after the general view of the different crystallographic systems; and 2ndly, the removal of the entire *general* discussion of circularly and elliptically polarized light from the Lecture on "Rotatory Polarization," to its proper place in immediate connection with the rest of the theory of polarization on the principle of undulations, — where in fact the author had commenced some examination of it, but had left it incomplete in that place, to go into its details in a subsequent Lecture in connection with the rotatory properties of quartz and other substances. This property indeed had been included under the common title of "Circular Polarization," by other writers, to the no small confusion of the subject, and probable perplexity of the student: I have, therefore, made this discussion of so remarkable an *application* of the theory of circular polarization to stand quite distinct from its *principles* under the far preferable title of "Rotatory Polarization."

By this change I must confess the due *proportions* of the several Lectures are somewhat impaired; but I conceive that, however important in the delivery of *lectures*, in a work for *reading* this will be of little consequence, in comparison with the greater facilities thus afforded to the student in point of clearness of conception, and due arrangement of the deductions.

In many instances I have annexed additional remarks and illustrations of my own. These seemed to be in some instances called for when some point was left in obscurity, on which I conceived the student might find further information desirable, or where more recent discoveries had led to modifications of previous views. In these illustrations, I have studiously adhered to the rule of simplicity and brevity: I have, however, been careful to refer the reader to the sources of full information. Among such illustrations I have mentioned one or two of an experimental kind, and of which I believe no account has hitherto been published. All such additions are distinguished from those made by the author, by being enclosed in brackets [ ]. On the whole, I trust it may be found that I have carefully adhered to the professed design of rendering the work more extensively useful for popular reading, and elementary instruction, without extending it to too great a length or to topics of too abstruse a kind; and subject to the especial restriction that it was designed for readers *not* versed in mathematics.

It may be right to add that the Lecture on the Microscope, appended to this volume, was left by the author in an obviously unfinished state; yet I did not feel at liberty to omit it, though certainly some explanation is due to the reader for its apparent imperfections,— as well as to the more scientific, for its extremely elementary character. This, however, will probably form no ground of complaint to the many: and the author no doubt judged soundly in affording even such rudimentary instruction to great numbers who are interested in the use of the Microscope and the contemplation of the wonders which it brings to light.

BIOGRAPHICAL NOTICE

OF

THE AUTHOR.

IT is not here intended, and indeed would be altogether out of place, to offer any detailed memoir of the Author of the following work: but his readers may be interested in possessing some slight record of his labours; especially with reference to the circumstances under which these Lectures were delivered. In drawing up this very slight sketch, the Editor has availed himself of several memoirs in different journals: and for information on several points, begs to acknowledge his obligations to Dr. SHARPEY, Sec. R.S., Prof. REDWOOD, JACOB BELL, Esq., and E. W. BRAYLEY, Esq.

JONATHAN PEREIRA (descended from a Portuguese family, his father having settled in London for commercial business) was born May 22. 1804. Receiving only an ordinary school education, he was apprenticed at fifteen (1819) to a medical practitioner, but quitted the situation in three years, owing to his principal becoming insane. During this period of leisure, as indeed all along, he diligently seized all opportunities of improvement; and now attended lectures at the Aldersgate Street Dispensary and St. Bartholomew's Hospital. In 1823, he was appointed Apothecary to the former institution and in 1825 Lecturer on Chemistry there. In this situation he published several elementary works for the assistance of students. In the same year he obtained his diploma from the College of Surgeons, and in 1828 was elected Fellow of the Linnæan Society.

His Chemical Lectures were of a more scientific kind than those usually given in the Dispensary; the indefatigable industry and zeal with which he followed up every research connected with the subject of his Lectures, was more strikingly evinced by his simultaneously taking lessons in the French and German languages, to enable him the better to avail himself of the labours of the continental chemists.

In 1832 he resigned the office of Apothecary to the Dispensary, and received from the Governors a handsome testimonial to his valued services. In the same year he commenced general practice, took a house in Aldersgate Street, and married.

In the winter of 1832-3, he succeeded Dr. Gordon, as Lecturer on Chemistry at the London Hospital, and at the same time joined the new Medical School in Aldersgate Street, as Professor of Materia Medica. Here so great was the influx of pupils, as at length to render it necessary to build a new theatre for their reception—an undertaking which he spiritedly carried through at his own expense. These Lectures, conducted on a scientific and extended plan, may be considered as having laid the basis of his reputation. They attracted the attention not only of students, but of practitioners; and at the request of the editor of the *London Medical Gazette*, the substance of them was in the first instance published in successive numbers of that journal in 1835-7, but subsequently he recomposed them with greater care, and in 1839 published the first volume of his great work, "The Elements of Materia Medica and Therapeutics;" a portion of the second volume appeared in 1840. And by the general testimony of the profession it has been recognised as a standard book. There was a speedy call for a second edition, and the work was also translated into German and other languages.

Some time after he was asked to accept the chair of Chemistry and Materia Medica at St. Bartholomew's Hospital, but as some deviation from strict rule would have been involved, to which his scrupulously honourable feelings could not consent, he at length declined the situation.

Notwithstanding his success in the Aldersgate Street School, he was, however, soon led to resign its duties, and in 1840 had determined on quitting London for two years, with the intention of graduating in one of the Scottish Universities. This intention, however, was superseded on a vacancy occurring in the office of Assistant-Physician to the London Hospital, for which he was induced to become a candidate. But for this purpose it was necessary to obtain the licence of the College of Physicians;—and this too with hardly any time to prepare for the requisite examination. Here, however, the extraordinary vigour of Mr. Pereira's mind triumphed over every obstacle; and with his already high attainments and unremitting labour, in the space of little more than a week, he so amply qualified himself as to pass with the highest credit. He soon after received the diploma of M. D. from the University of Erlangen:—and in March, 1841, obtained the appointment at the London Hospital without any contest.

In 1839, he had been elected a Fellow of the Royal Society, and in the same year, on the incorporation of the London University, his recognised merits secured him the appointment of Examiner in Materia Medica and Pharmacy; and his practice having largely increased, he removed to a house in Finsbury Square. His increasing avocations at length induced him to resign a portion of the labours of his chemical lectures at the Hospital, and eventually the whole of them, in 1846.

Having joined the Pharmaceutical Society, he lectured to that body on articles of food; and in 1843 published the substance of these Lectures in a separate work on "food and diet," which has been characterised, by competent medical authority, as one of the most able and philosophical treatises on the subject: and about this time, besides large contributions to the *Pharmaceutical Journal* and other professional periodicals, he was much and actively engaged in the promotion of various institutions for the diffusion of knowledge, especially the City of London Literary and Scientific Institution.

In the same year he became Professor of Materia Medica to the Pharmaceutical Society, and was indefatigable in researches into the nature, history, origin, and chemical composition of the various substances employed as drugs, contributing many papers on these subjects to various journals.

Dr. Pereira was of an eminently inquiring and comprehensive turn of mind, and with persevering industry followed up whatever subject he undertook. Devoted in the main to objects strictly professional, he yet occasionally diverged into collateral topics, though chiefly only where they had some bearing on the more pressing requirements of professional study. It was in this point of view that he appears to have taken up the study of crystallography, and more especially that of *Light*. The former, in its close and natural connexion with chemistry, would directly interest a mind engaged in chemical researches, and might in consequence be regarded as having some direct bearing on medicine. The latter subject, indeed, might seem at first sight entirely remote from all such application; yet there is one point in which it presents a singular and unexpected relation to medical science, viz., in the peculiar modification impressed on polarized light by certain fluids, both chemical and organic, and especially under certain morbid conditions of the latter. And in general, the relations of polarized light to the molecular structure of bodies, especially of organic substances, present many topics of physiological interest.

But independently of such applications, doubtless to a man of Dr. Pereira's enlarged views, it must have appeared that there is no branch of liberal science really alien to the highest education even of a strictly professional kind; and it was no doubt under this impression that he introduced considerable notice of these subjects into his Lectures at the London Hospital, in connexion with chemistry. This applies to several years previous to 1843. Indeed, at an earlier period, Dr. Pereira had given much attention to the subject.

In 1838, he was in correspondence with the writer of this notice, and, at a subsequent period, with several philosophers of high eminence, on the subject of Light; and in the spring of 1843, he delivered a course of Lectures on Polarized Light, prefaced by a short account of optics in general, and including a compendious view of crystallography, before the members of the Pharmaceutical Society.

The substance of these Lectures was published in the *Pharmaceutical Journal,* and reprinted thence in a separate volume in the same year, and the course was repeated in subsequent seasons.

At the period of the author's death, a copy of this work was found interleaved with numerous MS. notes, additions, and illutrations ; besides various memoranda, &c. On one of these occurs the date, October, 1844, which it is probable, refers to an enlarged course delivered in the School of the London Hospital.

Recognising the essential use of the microscope in medical researches, he gave, in 1850 or 1851, an elementary Lecture on the construction and use of that instrument to the Pharmaceutical Society: of this Lecture only some rough MS. notes have been preserved. They are appended to the present volume.

He was elected Fellow of the College of Physicians in 1845, and soon after Curator of its Museum ; and in 1849 commenced the third edition of his "Elements, &c.," in which year the first volume appeared, and the first part of the second in 1850. He was occupied in completing this great work up to the period of his death.

In 1851, becoming full Physician to the London Hospital, he resigned the chair of Materia Medica, but gave a few clinical Lectures in that institution. In December, 1852, while examining some preparations in the Museum of the College of Surgeons, he fell on a stone staircase, and injured a muscle of both thighs, so as to render him incapable of moving without assistance; and though confined to his room, it has been a point of much doubt, whether it was in any way connected with this accident, that on January 20, 1853, suddenly feeling pain, he exclaimed, "I have ruptured a vessel of the heart," and within half an hour expired, in the forty-ninth year of his age. His remains were interred in the cemetery at Kensall Green, amid a concourse of friends and pupils.

Of Dr. Pereira's high professional merits and personal character, it would be out of place here to speak. They have been amply recognised in the various journals dedicated to that profession of which he was so great an ornament. But it is in a subject like that of the following work, lying out of the direct line of his profession, and in the zeal and ability with which he mastered its details, so as to enable himself to become a most efficient and popular instructor of others, that we more signally recognise the activity and power of mind which was so conspicuous a characteristic of his intellectual constitution.

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ON

THE POLARIZATION OF LIGHT,

&c. &c. &c.

LECTURE I.

I HAVE been led to undertake the delivery of the following lectures on the Phenomena of Polarized Light, in the belief that their singularity, variety, splendour, and useful applicability will create great and universal interest in the minds of my auditors, whatever be their pursuits, occupations, or acquirements.

I am acquainted with no branch of experimental philosophy capable of presenting such brilliant and gorgeous phenomena, and which are so well adapted for illustration in the lecture-room, as polarized light. In its power of unfolding to our view the intimate structure and constitution of natural bodies, it certainly has no superior, if indeed it have any equal. It furnishes us with characters for recognising and distinguishing many bodies; and it gives us the means of determining the nature of the changes going on in some of the recondite operations of nature. It is a subject whose phenomena are so complicated and intricate, that it not only admits of, but actually requires the highest departments of mathematics to elucidate them; and it is therefore very properly placed in the very first rank of the physico-mathematical sciences.

But in all societies and associations, the lovers of knowledge are of two kinds, philosophers and utilitarians. The first pursue science for its own sake; the second, for its usefulness. With the latter, every step they take in the acquirement of knowledge is accompanied with the question "*cui bono?*" With such, all scientific researches which have no immediately practical bearing, which, according to their narrow views, cannot be at once shown to be *useful*, are neglected, perhaps even sneered at. Though with such I profess to hold no community of feeling, yet, as I am desirous of combining in these lectures the *utile* with the *dulce*, I think I can venture to hold out to them ample remuneration for the time they may devote to the study of polarized light by attending these lectures.

If I can show them that this agent furnishes us with a more intimate knowledge of the nature and properties of many substances; if I can demonstrate its applicability to the detection of adulteration of foods, drugs, and chemicals; if I can point out its application to the determination of the commercial value of saccharine juices; if I show how it has been applied to determine the nature of the changes which occur in certain chemical and vital processes, in which ordinary chemical analysis completely fails us; if I prove that it may aid members of my own profession in detecting the existence of certain diseases; and, lastly, if we show the possibility of its use to the mariner, in aiding him, under certain circumstances, to avoid shoals and rocks—I trust even the utilitarians will admit that the study of polarized light is both advantageous and profitable, and that our time has not been unprofitably occupied by these lectures.

These are only a portion of the valuable and practical uses of which polarized light is susceptible. Its phenomena are so intricate, and at present so little understood by the public, that a very large number of persons who might otherwise, perhaps, beneficially avail themselves of its services, are ignorant alike of its powers and of its uses. We may therefore hope that, when it becomes better known, it will be found more extensively useful.

Common and polarized light agree in several of their leading properties; and though these lectures are intended to illustrate the peculiarities of polarized light, yet, before we can prove what is peculiar to the one, we must be acquainted with the general properties of the other; and thus, I conceive, I must introduce polarized light to your notice by *a preliminary general view of the physical properties of light.*

Moreover, the phenomena of polarized light are so numerous, various, and intricate, that the student is very apt to become bewildered with an immense multitude of facts, and to forget, if indeed he ever knew, the conditions which are requisite for the production of each phenomenon. Hence, then, it becomes desirable that we should give him some artificial aid to assist in the conception of facts and the modes of observing them, as well as to show him how these manifold phenomena are mutually connected and dependent. We require, in fact, some means of generalisation. Such will be found, I think, in the *undulatory hypothesis of light.*

With regard to the former of these objects, we will first observe that, by the term "*light*" we understand the cause of vision, or that which enables bodies to manifest themselves to us through the eye.

This implies some agent or influence emanating from those bodies which are self-luminous, and by means of which other bodies not luminous are rendered visible. Etymologically from φως, light, referring more objectively to the *cause* of vision, we derive the terms Photometry, Photology, Photography; speaking more subjectively, we have Optics, from οπτω, *I see.* To this wonderful agent, combined with the beautiful adaptation of our organs to it, we owe the enjoyment of that most useful and important function of our daily existence by which we become acquainted with the *forms*, *colours*, *positions*, and *motions* of bodies, so essential to all our active employments. It improves and facilitates our intercourse with our fellow-creatures, and is a powerful auxiliary to the proper performance of the other senses. When we aid this sense by the instruments with which science has furnished us, it leads us to the contemplation of two kinds of infinity which would otherwise have remained unknown,—infinite minuteness in animalculæ and innumerable other objects imperceptible on account of that minuteness; and infinite magnitude evinced in the celestial bodies, invisible by reason of their remoteness: thus opening to natural history a new field, to astronomy a new heaven, and inviting and enabling us successfully to contemplate the universe of the poet,

> "Without bound,
> Without dimensions, where length, breadth, and height,
> And time and place, are lost."

And, by way of a more precise *illustration* of these remarks, we may notice that we are enabled, on the one hand, to measure spaces less than $\frac{1}{250,000,000}$th of an inch; and, on the other, to penetrate distances extending to millions of miles, such as those of the planets and some fixed stars which are susceptible of exact determination; and to yet more inconceivably immense depths of space in those remoter stars and nebulous worlds beyond all reach of measurement.

With regard to the second point referred to, before I proceed to state the properties of light, I think it right to allude, in general terms, to the chief hypotheses or theories which have been proposed to explain its phenomena.

1. The *Newtonian hypothesis*, or the *projectile* or *emission theory*, was started when our knowledge of the facts was but in its infancy, and has but a very limited application to them. It supposes light to consist of small particles which are constantly emitted from luminous bodies, and which move in straight lines. These particles enter the eye and impinge on the

retina. By this means some peculiar effect is produced, which being transmitted along the optic nerve to the brain, gives us the sensation of light. The particles vary in size, those producing *red* being the largest, while *violet* is produced by the smallest.

2. The *wave* or *undulatory hypothesis*, originally adopted in a very crude form by Huygens, Descartes, and Hooke, was in later times reduced to more accurate principles by Young, and more fully developed by Fresnel and his successors. In this country, Herschel, Airy, Lloyd, Powell, and M'Cullagh have greatly contributed to its advancement and adoption.

It accounts for the phenomena of light by referring them to waves of an imaginary fluid called *ether*, as sound is referable to waves of ponderable matter, and especially of the air. The difference of colour depends on differences in the length of the waves: *red* is produced by the longest, *violet* by the shortest.

The vibrations of this ether being communicated to the retina, excite an effect which is propagated along the optic nerve to the brain. On this theory, then, nothing enters the eye. But the motion of the ether without the eye is propagated to the ether within the eye: the latter affects the retina. On the projectile theory, something is assumed to leave the luminous body, to travel with almost incalculable velocity, and to enter the eye like a shot from a musket or cannon.

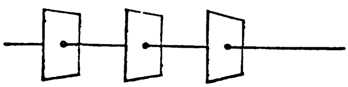
These general observations on the two most celebrated theories or hypotheses are all that at present it will be necessary to bring before you. Hereafter we shall enter more fully into the subject.

Whichever theory we adopt, we must assume in all our reasonings that *light consists of separable and independent parts.* This property of light is readily established by familiar experience. Any portion of light may be intercepted by an opaque obstacle, and the rest allowed to pass; and this latter part is never found to be affected in any way by its separation from that which is intercepted. The smallest portion of light which we can thus intercept or allow to pass, is called a *ray.* (Lloyd, *On Light and Vision,* 1. and 2.)

I will now proceed to enumerate the chief particulars which constitute the peculiar characteristics of light.

I. *The Propagation of Light.*—Light emanates, radiates, or is propagated in straight lines, as is familiarly proved by making holes in three disks,

Fig. 1.



which must lie in one straight line for light to pass through them.

The straight lines, or the directions in which light is propagated, are called the *rays* of light: any sensible portion of light must contain an infinity of *rays*, which when parallel are often called a *beam* of light. So a bundle of converging or diverging rays is called a *pencil:* but this last term is also frequently applied as well to parallel rays.

The propagation of light takes place with inconceivable rapidity:

	per sec.	per min.	per hour.
At the rate of } Miles	192,500 × 60 =	11,550,000 × 60 =	693,000,000.

This has been ascertained in two ways: —

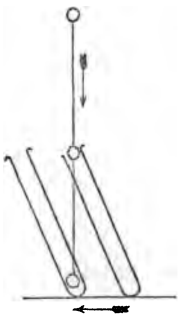
1st. *By Eclipses of Jupiter's Satellites.* In 1676 Roemer, a Danish astronomer, observed, that the eclipses took place *too soon* at one season when Jupiter was nearest to the earth, and *too late* at another season when he was farthest off. The difference of time was $16' \; 26'' \; 6'''$. This he inferred was the time light took to travel across the earth's orbit, a distance of 190,000,000 miles.

According to Struve, the velocity of light is 191,077 miles [166,072 geographical miles] per second. (*Humboldt.*)

2dly. *From the Aberration of Light.* This is a small apparent deviation of the fixed stars, by which they sometimes appear 20″ distant from their true situation. The cause of it was first explained by Dr. Bradley in 1747, though he discovered the fact in 1727. It depends on the combined progressive motion of light and the earth's annual motion in its orbit.

The nature of this effect may be illustrated by the instance of a shower of rain falling perpendicularly on a man standing still, and on another running forward; the latter of whom receives the drops striking *against* his face, though they actually fall truly perpendicularly. And the cause of this will be explained if we consider the case of a ball falling on the open mouth of an inclined tube at rest, when it would simply strike against the lower inner surface: and then suppose the tube at the same inclination carried forward at a proper rate, when the ball will descend to the bottom of it; the *telescope* and the *eye* being represented by this tube, moving forward along with the earth.

Fig. 2.



This method gives 191,515 miles per second as the velocity of light, and is preferred by the best astronomers, as more accurate than the former.

By way of *illustrations of the velocity of light compared to the velocity of other bodies,* we may take the following instances: —

1. *Railway carriages.* These travel at from 30 to 40, or even at 60 miles the hour. Take the latter, the maximum speed. At 60 miles an hour, a railway carriage would require above 180 years to reach the sun; *light* accomplishes the distance in 8 minutes and 13 seconds.

2. *Cannon balls.* A cannon ball would require 17 years at least, to reach the sun, supposing its velocity to continue uniform from the moment of its discharge. (*Herschel.*)

3. The *pendulum.* Light would travel eight times round the earth during a single beat of a common pendulum.

4. The planet *Mercury* moves in its orbit with a velocity of 30 miles per second; light travels with more than 6000 times that velocity.

TIME OCCUPIED BY LIGHT IN TRAVERSING THE HEAVENS AND TRAVELLING FROM THE HEAVENLY BODIES TO US.

Time required for Light to travel to us from the—

Moon		about 1¼ second.	
Sun		8 minutes, 13 sec.	
Georgium Sidus		about 2½ hours.	
Fixed stars of ascertained distances	1. α Centauri	3 years.	(*Humboldt.*)
	2. 61 Cygni	9¼ years.	
	3. α Lyræ	12 years.	
Sir W. Herschel's remotest nebulæ		2,000,000 yrs.	(*W. Herschel.*)

Until very recently, the distances of the fixed stars were entirely unknown to us; at present, those only of a few of the nearest have been measured.

The calculations of the probable times required for light to travel from these bodies to us, are almost overwhelming in their results. Consider for a few moments some of the consequences of the facts we thus ascertain:—

1st. When we contemplate, on a clear night, the heavenly vault, the phenomena which present themselves to our notice belong to past times of most unequal distance from us; from 1¼ second (that of the moon) to 2,000,000 of years (that of the remotest nebulæ visible by the aid of a telescope). We contemplate as it were an historical chart, in which events the most distant in point of time are grouped side by side, and presented to our notice at the same instant. The lights issuing from the heavenly bodies, and traversing cosmical space, "reach us as voices of the past."

2ndly. Many of the celestial bodies which the astronomer is now calmly contemplating, may have ceased to exist ages ago; in fact, long before they became visible to our eyes. The Georgium Sidus would be visible to us for more than two hours after its existence had ceased, while Herschel's nebulæ would be perceptible for two millions of years after their destruction!

3rdly. The heavenly bodies which become successively known to the astronomer as fresh discoveries, may have had a successive origin in the heavens thousands of years ago, but only now have become visible to us by the arrival of light after its prolonged journey from the newly formed cosmical body to us.

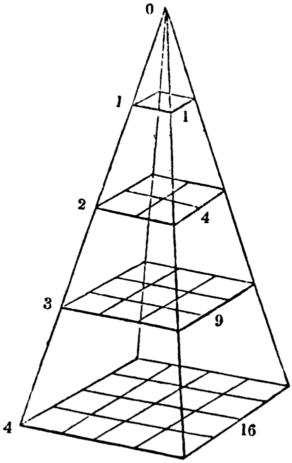
4thly. Light, probably, furnishes us with the best evidence we can obtain of the great age of matter. Human historical records of our earth do not extend further back than 5000 or 6000 years. The geologist gives us proof that the age of the earth is, in fact, much beyond this, but does not furnish us with facts on which we can venture to guess even at the distance of time which has intervened between different geological epochs. But when we survey the starry heavens, our telescopes penetrate not merely space, but time. They reveal to us ancient bodies and phenomena, whose age they enable us also to estimate; and thus we arrive at the conclusion that "the light of the most distant cosmical bodies offers us the oldest sensible evidence of the existence of matter."

II. *Variation of Intensity.*—The intensity of light decreases as the square of the distance increases: at twice the distance, it has only $\frac{1}{4}$ of the intensity, at thrice the distance $\frac{1}{9}$ the intensity, at four times the distance $\frac{1}{16}$ of the intensity, and so on.

The reason of this is, that emanating equally in all directions from any point, it illuminates four times the space at twice the distance, nine times at thrice, and sixteen times at four times the distance; hence, its intensity must be inversely as the square of the distance.

The law is aptly illustrated by a quadrangular pyramid supposed to be divided horizontally, at equal distances, into four parts or segments of equal height. The upper segment has a square base, whose area we shall call 1; the second segment has also a square base, but its area is 4; the area of the square base of the third segment is 9; and that of the lowest or fourth segment, 16. Here the distances of the bases of the segments from the apex of the pyramid are as 1, 2, 3, 4, while the areas of these bases are as 1, 4, 9, 16.

Fig. 3.

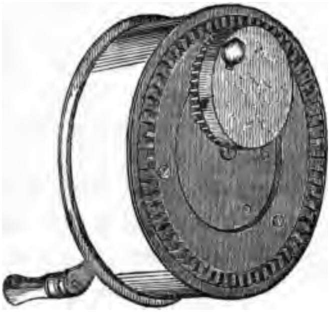


The readiest demonstration of the law for the lecture-room is the following:—Let the light from a lantern pass out through a square aperture, and be received on a semi-transparent screen divided into square spaces. Notice at what distance the beam of light illuminates one of these squares; at double the distance it will illuminate 4, at triple 9, at quadruple 16 squares.

In *Photometry*, we avail ourselves of this law. If two luminous bodies, at unequal distances, produce the same amount of illumination, the relative quantities of light evolved by these bodies are as the squares of the distances. Thus, if a lamp, at four feet distance, give as much light as a candle at one foot, the lamp actually evolves 16 times as much light as the candle. Count Rumford's photometrical process of observing at what distances two lights gave two shadows of equal intensities, as well as the photometers of the late Mr. Ritchie and of Professor Wheatstone, are on this principle. But all these modes of measuring light are objectionable, since they are based on the imperfect and varying judgment of the eye.

Professor Wheatstone's photometer is a very ingenious contrivance. It is a cylindrical box, of about two inches diameter, and one inch in depth, and which contains a system of two wheels and pinions. On the face of the box, and near to its external border, is a circle of cogs. In the centre of the face is an axis, to which is attached an horizontal arm, carrying a toothed wheel or disk, the teeth of which fit into the cogs of the outer circle. This wheel has a double motion—it rotates on its own axis, and also revolves within the cogged circle. To this disk is attached a small, hollow, glass bead, silvered internally, and which moves with great rapidity backwards and forwards across the face of the cylinder. The motion is communicated by turning the handle on the opposite face of the box. If this photometer be placed between two lights, and the bead put in rapid motion, we observe two parallel luminous lines, about the $\frac{1}{10}$ of an inch apart. By adjusting the relative distances of the two lights from the photometer, so that the brightness of the luminous lines may be equalized as determined by the eye, and then squaring the distances, their comparative intensity may be ascertained.*

Fig. 4.



Wheatstone's Photometer.

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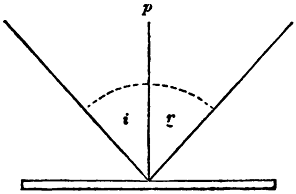
* This instrument is made by Messrs. Watkins and Hill, of Charing Cross.

III. *Transparency and Opacity.*—Some bodies allow light to penetrate them, as air, water, glass, crystal, &c. These are called *transparent* bodies. Others, refuse to give passage to light, as the metals. The latter are termed *opake* bodies. But some substances, which in the mass are opake, become transparent when reduced to thin films. Gold is an instance of this: in the lump it is opake, but as gold leaf it allows light to traverse it.

IV. *Reflection.*—When a beam of light falls on a smooth-polished surface, a portion of it is *reflected.* The incident and the reflected ray make each the same angle with the reflecting surface, hence the law of reflection is, that *the angles of incidence and reflection are equal.* This law holds good under all circumstances, whether the reflector be plain or curve. The incident and reflected rays are also always in one and the same plane.

Thus in (*fig.* 5.) drawing a perpendicular p to the surface, i is the angle of incidence; r is that of reflection and $i = r$.

Fig. 5.



A polished metallic plate, as a *speculum,* is a good reflector. *Glass,* being transparent, reflects both from its anterior and posterior surface. Hence in some optical experiments, where it is desirable to avoid the confusion from a double reflection, the posterior surface of the glass is either *ground*, or *blackened* by means of soot, candle-smoke, or size and lamp-black. This proceeding is especially desirable in experiments on polarized light. *Silvered glass*, that is, glass covered on the posterior surface by an amalgam of tin, as the common looking-glass, is not adapted for accurate optical experiments, on account of the reflection from the metal as well as from the glass.

V. *Refraction.*—When a ray of light passes obliquely out of one medium into another of a different kind, it changes its direction, or is bent out of its course; in optical language, it is *refracted.* The different nature of bodies in this respect is usually characterised by density, but also by other conditions; among which combustibility is one; it was from the high refractive power of diamond that Newton boldly conjectured its inflammable nature. If the second medium be denser, or as it is termed of higher refractive power, than the first, the refraction is *towards* the perpendicular; but if the density or refractive power of the second medium is less than that of the first, the refraction is *from* the perpendicular: but always in the same plane.

If the ray fall perpendicularly on the refracting surface, it suffers no change in its direction; in other words, it undergoes no refraction.

In most optical instruments in which refracting media are required, *glass* is employed, as in the camera obscura, astronomical and terrestrial telescopes, microscopes, magic lanterns, common spectacles, eye-glasses, &c. The oxyhydrogen apparatus which I shall use in these lectures for illustrating the phenomena of polarized light, serves, when deprived of its polarizing part, for use as a microscope (*oxyhydrogen* or *gas microscope*), the images of the objects being thrown on a screen. Used in this form, it is simply a refracting instrument. Its structure I shall hereafter explain. *Quartz* or *rock crystal* is used, under the name of *Brazil pebble*, as a refracting medium for spectacles, on account of its greater hardness, and its being less liable to scratch. The *diamond* and other precious gems have been occasionally used for microscopic lenses. Jewellers employ a *glass globe filled with water*, to concentrate the rays from the lamp which they use to work by. The water is generally coloured pale blue, to counteract the reddish yellow tint of the artificial light. *Amber*, when cut and polished, is sometimes used for spectacles.

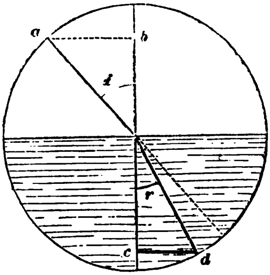
I have already stated, that the law of reflection, as regards the direction of the reflected ray, is the same for all reflecting media. But the law of refraction is very different, each refracting medium having its own peculiar action on light.

A variety of curious and well known phenomena result from the unequal refracting powers of different bodies, or of the same body in different states of density. Thus the apparent crookedness of a stick placed obliquely in water; the difficulty of hitting a body, as a fish, in water, when we take an oblique aim; the deception experienced in estimating the depth of water, except when viewed perpendicularly; and the altered position of a body (as a piece of money) at the bottom of a basin, when viewed obliquely, first when the basin contains no water, and afterwards when water has been put in; — these, and many other phenomena, result from the greater refractive power of water than of air, and the consequent change of direction which the luminous rays suffer when passing from one medium to the other. Again, the tremulous motions of bodies, when viewed through an ascending current of heated air, and by which an excise-officer is said to have, on one occasion, discovered a subterranean still in the Highlands of Scotland, result from the unequal refracting power of air in different states of density.

[Light passes freely through air, which nevertheless possesses an exceedingly small refractive power, sufficient however to be very sensible in altering the apparent places of the heavenly bodies when seen obliquely through the whole thickness of the atmosphere.

The quantitative law of refraction is that, on passing out of a rarer into a denser or more refracting medium, " the sine of the angle of incidence is to that of refraction in an invariable ratio for the same ray and the same medium;" this ratio is called the "refractive index" or "refractive power" of that medium. Thus in the annexed diagram (*fig.* 6.), *i* is the angle of incidence, *r* that of refraction; and imagining a circle described about the point of incidence, *a b* is the sine of incidence, *c d* that of refraction.

Fig. 6.



For water, if $c\,d = 1{\cdot}000$,
then $a\,b = 1{\cdot}336$;

hence the index of infraction for water is 1·336, and the general formula is $\sin. i = m \sin. r$, m being the index of refraction.

This great law, the foundation of all optics, was discovered by Snell, in 1619.

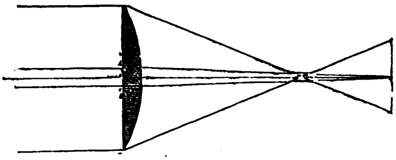
The point where several rays cross after undergoing reflection or refraction, is termed a "focus." A lens is usually a piece of glass, contained by small portions of two spherical surfaces, either convex or concave.

If rays issue from one point, such as a small luminous object at a certain distance from a convex lens, they will, on being refracted through it, converge to another point on the other side of it, whose distance is determined by the distance of the first point, or origin, and the refractive power of the lens: two points so related are called "conjugate foci."

If the rays come from a *very* distant object so that they are sensibly *parallel*, the focus to which they converge is called the *principal* focus.

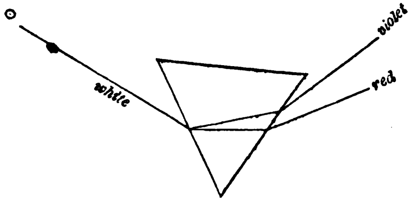
Generally, the focus will be nearer to the lens, or its focal distance shorter, as its surfaces are more curved. But if we trace accurately the course of the rays, it is easily found that, though they converge *very nearly* to one point, they cannot do so accurately, those which pass nearest the centre of the lens will converge further off, and those towards the edges nearer. This difference is called the spherical aberration. (See *fig.* 7.) This defect may be remedied by certain combinations of spherical surfaces of different radii. It is also materially diminished by limiting the area of the rays to the central portion by a "stop" or diaphragm, with a circular hole in the middle. In the eye the iris or pupil answers this purpose, also in the crystalline lens the aberration is counteracted by the remarkable provision that the central portion is more dense, and thus the different rays are more equally refracted.]

Fig. 7.



VI. *Dispersion.*— If a ray of white light be made to traverse a refracting medium, or, in other words, to suffer refraction, it is found to have undergone a remarkable change—it is no longer perfectly white, but more or less coloured. It is inferred, therefore, that white light is made up of coloured lights, and that these, being unequally refrangible, are separated, or, in optical language, are *dispersed*. In this way, a series of colours is obtained, which have been commonly distinguished into seven principal tints, viz. *violet*, *indigo*, *blue*, *green*, *yellow*, *orange*, and *red*. These are procured by a triangular piece of glass, called a prism, in which the dispersion at the first surface is greatly increased on emergence at the second (see *fig.* 8.)—the colours constituting the *prismatic* or *solar spectrum*. These colours result from the *decomposition*, the *analysis*, or the *dispersion* of the white light of the sun. If we allow the oxyhydrogen lime-light to pass out of the lantern through a slit, and receive it on a prism, a very similar spectrum is formed and may be thrown on the ceiling of the lecture-room, or on the screen before us. The light of a lamp or candle gives only a faint spectrum with a larger proportion of red.

Fig. 8.



To persons unacquainted with philosophical investigations, few facts seem more astonishing, and even improbable, than that of *white* light being compounded of differently *coloured* lights. I shall, therefore, dwell for a few minutes on this topic.

Every one is familiar with the fact, that by mixture artificial colours are altered. Thus blue and yellow form *green;* red and yellow form *orange;* while blue, with different proportions of red, yields *indigo* or *violet.*

It has hence been a speculation of some philosophers that of the so-called seven prismatic colours into which the prism decomposes white light, three only may be primitive, and four compounded.

Primitives.	Compounds.
Red	Orange
Yellow	Green
Blue.	Indigo
	Violet.

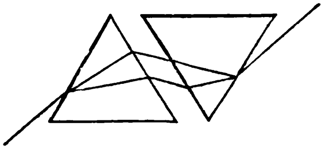
[But this is at variance with the fact, that the more *pure* and the more *perfectly* dispersed the spectrum is, the more distinct are all the shades of colour, each of which must therefore be in itself a primitive tint, and not a compound of others. The fact is, the number of primary rays is not really seven, but infinite.]

If the seven prismatic colours be painted on a circular disk of card, in their proper proportions, which is then made to rotate rapidly, the union of these colours on the retina gives us an impression of greyish-white.

If we paint the three supposed primitive colours, viz., red, yellow, and blue, on a similar disk, and cause this to revolve, we also obtain an impression of greyish white. But these pigments are none of them pure prismatic tints.

These experiments favour the notion, that the sensation of white light depends on the simultaneous impression of differently coloured lights on the retina. [The simplest and most direct proof consists in this: if we take *two* equal and similar prisms of the same kind of glass, the ray of light which passes through the first of them is decomposed into colours, and if these be now received on the 2nd prism placed in an inverted position, they will in that prism retrace their course and be united again, and emerge in a ray of *white* light; or in one word, if we look through such a combination, we see objects *uncoloured;* yet we know that they must have become coloured in their passage.] Hence, white light is *compound* or *heterogeneous light*,

Fig. 9.



while the component prismatic colours are *simple* or *homogeneous lights*. Each of these may be termed a *monochromatic light*.

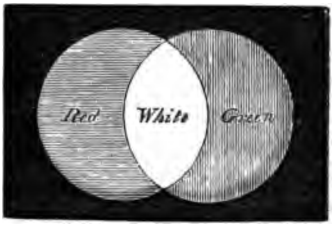
It follows from this view of the subject, that two *mixed* colours may, by their union or mixture, produce white light. Colours or tints which do this, are called *complementary*.

Brewster's table of Complementary Tints.

Red	Bluish green
Orange	Blue
Yellow	Indigo
Green	Violet reddish
Blue	Orange red
Indigo	Orange yellow
Violet	Yellow green
Black	White
White	Black.

A beautiful illustration is afforded, if we throw two beams of coloured light, one red, the other green, on a screen, when we see two circular disks of coloured light, and by making them overlap, they pro-

Fig. 10.

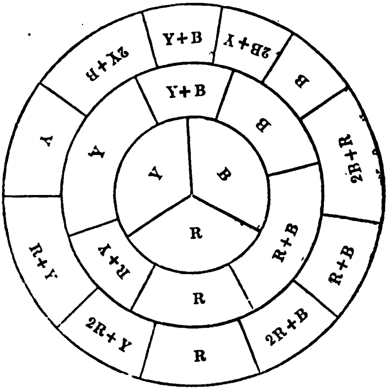


Formation of White Light.

duce white light. A similar result (that is, the formation of white light) is also produced by the overlapping respectively of disks of indigo and yellow, and of blue and orange. These colours are not identical with the pure red and green of the solar spectrum, they are obtained by a complicated process, the nature of which will be fully explained hereafter.

Professor Henslow has some very interesting remarks on the *composition of colours*, &c., in *Botany*, p. 195, et seq.

Fig. 11.



B. Blue
2 B+R. Blueish purple or purplish blue.
B+R. Purple.
2 R+B. Reddish purple or purplish red.
R. Red.

$2\,R+Y$. Reddish orange or orange red.
$R+Y$. Orange.
$2\,Y+R$. Yellowish orange or orange yellow.
Y. Yellow.
$2\,Y+B$. Greenish yellow or yellowish green.
$Y+B$. Green.
$2\,B+Y$. Bluish green.

$B+R+Y=$ White light with the colours of the spectrum.

$B+R+Y=N$ or neutral or grey tint when material colours are employed.

Hence,

Green + Orange $=N+Y$. For $(B+Y)+R+Y=Y+(B+R+Y)=N+Y$.

Orange + Purple $=N+R$. For $(R+Y)+(B+R)=(B+R+Y)+R=N+R$.

Green + Purple $=N+B$. For $(B+Y)+(B+R)=(BRY)+B=N=B$.

Some philosophers have thought that the position of the orange or green lights in the spectrum favours the notion of their being mixed colours; since the orange is placed between the red and the yellow, and the green between the yellow and the blue.

But the indigo and the violet, being placed the most remote from the red, appear to present an obstacle to this notion. Sir D. Brewster, who adopts the supposition of there being three primitive colours, supposes that the solar spectrum consists of three spectra of equal lengths, a red, a yellow, and a blue one; and that the position of the maximum intensities of these colours varies, while certain portions of each of the three colours form white light, by mixing with the other colours in the requisite proportions—the excess of colour giving the predominating tint to that part of the spectrum where it exists. Thus in the red part of the spectrum there is an excess of red rays, in the yellow part of yellow rays, in the blue part of blue rays, in the violet part of both blue and red rays.

This view of the subject has never appeared to me satisfactory; and accordingly another and a more probable one presenting itself, I am inclined to adopt it, more especially as it is supported by some experiments recently made by Sir John Herschel.* Suppose a repetition of the primitive colours of the Newtonian spectrum, the red of the second spectrum being partially superposed on the blue of the first spectrum. The extreme blue rays of the first spectrum being intermixed with the red rays of the second spectrum, will give the sensation of indigo and violet. But it may be asked, where are the other colours of the second spectrum?

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* This notion was thrown out by Professor Grove, in his Lectures on Light, delivered at the London Institution, in November, 1842.

The reply is, that they are not visible to the eye. What evidence, then, it will be said is there of the existence of invisible rays beyond the first or Newtonian spectrum? The evidence is two-fold: first, the well known chemical effects produced beyond the visible spectrum; and, secondly, Sir John Herschel's experiments before referred to. In his first paper[*], in which he announces the extension of the visible prismatic spectrum, and the existence of a new prismatic colour beyond the violet, he states, that this colour appeared to his eyes, as well as to those of a friend, to be lavender-grey. But in a more recent paper[†], he appears to have satisfied himself that the colour is yellow. "And if such," he adds, "rather than lavender or dove colour, should be the true colorific character of these rays, we might almost be led to believe (from the evident reappearance of redness mingled with blue in the violet rays) in a repetition of the primary tints in their order, beyond the Newtonian spectrum; and that if, by any concentration, rays still farther advanced in the chemical spectrum could be made to affect the eye with a sense of light and colour, that colour would be green, blue, &c., according to the augmented refrangibility."

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[*] *Philosophical Transactions*, for 1840, p. 19.

[†] *Ibid.* for 1842, pp. 195, 196.

The following diagram serves to illustrate this view : * —

	Primitive Colours.	Mixed Colours.
Newtonian Spectrum……	RED………	
		ORANGE.
	YELLOW …	
		GREEN.
	BLUE ……	INDIGO.
		VIOLET.
Hypothetical Spectrum …	Red………	
		Orange.
	Yellow……	
	Blue………	Green.

There are many interesting topics connected with the spectrum, the details of which I feel precluded from entering into, inasmuch as these lectures are intended to illustrate the phenomena of polarized light. I must, therefore, content myself with briefly naming some of them. The first is the *unequal refrangibility* of the different-coloured rays; the red being the least, the violet the most refrangible. It is in virtue of this property that lenses and prisms produce the phenomena of *dispersion* or *chromatic aberration*. Newton thought that the size of the spectrum, or the dispersive power of the refractive medium, was proportional to its refractive power; and, therefore, that the refracting telescope could not be made *achromatic*. In this he was mistaken. Equal refractions do not produce equal dispersions. Two lenses made of different kinds of glass, as one of crown the other of flint glass, may be so ground that the dispersions shall neutralize each other, while their refractions, not being equal, cannot neutralize; consequently, an excess of one remains.

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* [The student should carefully observe the purely *conjectural* nature of those highly interesting speculations. It may be also a question whether they may not be materially affected by the recent discoveries of Professor Stokes.]

Chromatic Aberration.—Prisms, as we have seen, disperse as well as refract light. Now, lenses are comparable to prisms. A section of a convex or a concave lens resembles somewhat two prisms, in the one case set base to base, in the other edge to edge (see *fig.* 12.).

Fig. 12.

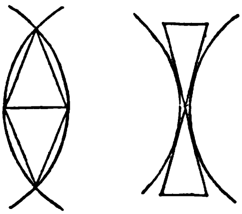
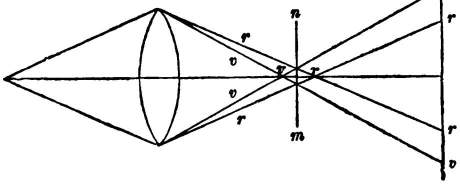


Fig. 13.

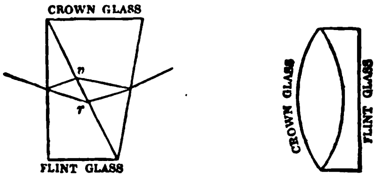


It follows, therefore, that they must *disperse* as well as *refract*. Hence they produce more or less colour. This is called *chromatic aberration*. See *fig*. 13. where the section of the rays at *n m* is the circle of least aberration.

This property was at one time thought to be fatal to the perfection of telescopes and microscopes; as by Newton.

Opticians obviate this defect by combining different media, such as different kinds of glass which have different dispersive as well as different refractive powers, into compound lenses, which are hence called achromatic (see *fig*. 14.).

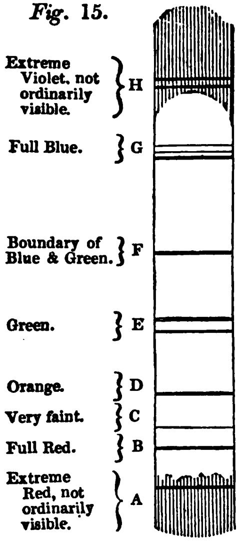
Fig. 14.



Under ordinary conditions we can see bodies without this colouring, and therefore our eye is practically *achromatic*. [But the case, though in some respects *similar* to that of optical instruments, is not the *same*, and depends on a slightly different application of theory in the combination of the refractive media. It is also probable, that the degree of achromatism differs widely in different individual eyes.*]

Not the least remarkable fact connected with the spectrum, is the existence of *bands* or *fixed lines* in it. Though originally discovered by Dr. Wollaston, they are commonly called *Fraunhofer's lines of the spectrum.* The best mode of seeing them is to examine the spectrum by a telescope. [The annexed figure (*fig.* 15.) may give a general idea of the appearance and position of a few of the most conspicuous lines as designated by Fraunhofer by the letters A, B, &c. It may be desirable to many students to know that the general fact of the existence of such lines, may be rendered evident by much simpler means than those used by Fraunhofer. It depends, however, essentially on the *goodness of the glass* of the prism, and affords a test of it. With most ordinary flint-glass prisms three or four at least, of the chief lines can

Fig. 15.


Extreme Violet, not ordinarily visible.
H
Full Blue.
G
Boundary of Blue & Green.
F
Green.
E
Orange.
D
Very faint.
C
Full Red.
B
Extreme Red, not ordinarily visible.
A

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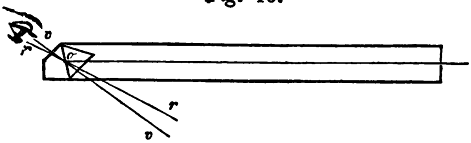
* See *Memoirs of the Oxford Ashmolean Society,* vol. i. 1838.

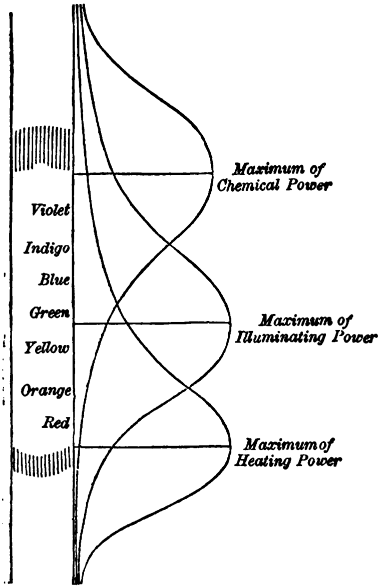
be readily seen, if we merely hold the prism close to the eye, and view the image of a narrow slit ($\frac{1}{20}$ inch wide) in a shutter or screen fixed in the upper part of a window through which the *white light of the clouds* passes. A very good plan is to make a tube three or four feet long covered at one end, with such a narrow slit in the cover, and having a short prism *shut* into the other end (so as to exclude all extraneous light), adjustable about its axis by a projecting end outside, and furnished with a small aperture or tube for the eye. The slit must also be adjustable to exact parallelism with the axis of the prism. These lines belong exclusively to the *solar* light; other kinds of light have lines peculiar to themselves.] Other systems of lines of a different kind are produced when the light of a lamp, or that produced by throwing the oxyhydrogen flame on lime, is passed through a bottle filled with nitrous acid vapour, before it falls on the prism.

Fig. 16.



The illuminating, heating, magnetic, and chemical powers of the spectrum—I must pass over without further notice, as they have no direct connection with the immediate object of this course of lectures. I cannot resist, however, remarking that the existence of a calorific, magnetic, and chemical influence beyond the confines of the coloured spectrum, is a fact of considerable importance in any inquiries which may be instituted into the nature of light. Moreover, the splendid and interest-

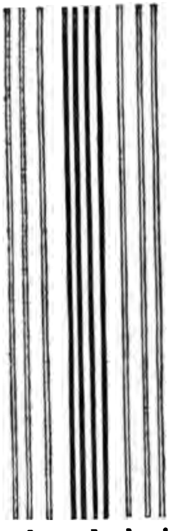
Fig. 17.



ing pictures called *Daguerréotypes*, *Calotypes*, *Chrysotypes*, and *Ferrotypes*, or *Cyanotypes*, produced by the chemical influence of light on gross or ponderable matter, show the high importance of investigations respecting the chemical powers of the spectrum. The relative positions and maxima of these sets of rays are represented in *fig*. 17.

VII. *Diffraction.*—When light passes near the edges of bodies, it suffers certain modifications, included by opticians under the denomination of *inflexion* or *diffraction*. If an opaque body be placed in a cone of light admitted into a dark chamber through a very small aperture, its shadow is larger than its geometric projection. Moreover, its shadow is bordered with fringes, and other parallel stripes are observed within the shadows of narrow bodies. *Fig*. 18. represents the appearance of the shadow of a wire under these circumstances; the outside fringes are slightly coloured, the interior are dark and white only, the centre band is always white; the number of bands depends on the thickness and distance.

Fig. 18.



If the light be homogeneous or monochromatic, the fringes consist of dark and light spaces of the same colour, and are of different breadths, red yielding the broadest, violet the narrowest fringes; in white light the fringes are consequently coloured with compound tints.

Coloured fringes may be readily observed by looking through the slit between the almost closed fingers, at a candle, placed at a distance of several yards. It may be seen still better by looking at the same luminous body through a feather, or through a fine wire-gauze.

When I tell you that the immortal Newton failed to perceive the internal fringes, and that he left the subject altogether in an imperfect, unsatisfactory, and unfinished state, I need scarcely add, that the phenomena are very complicated, and their study difficult.

[The most perfect method of exhibiting diffraction is by means of the sun's light, thrown into a darkened room by a mirror outside, and brought to a point at the focus of a small lens of short focus, exactly as in a solar microscope. The image of the shadows of the wires, edges, apertures, gratings, &c., can then be seen with their various fringes, brilliantly depicted on a screen, or still better, viewed by an eye lens of short focus, the screen being altogether removed;

this is by far the best method in all experiments of this kind.

The Editor has also found, that by a modification of this method the phenomena of diffraction may be seen by candle-light, on a minute scale, if we merely stretch a fine wire (about $\frac{1}{30}$ inch diameter) across the *surface* of the small eye lens or even near to it, but within the distance of its focus, and then look through the lens from the other side, at the flame of a candle at a distance of at least twelve feet, the wire being parallel to the length of the flame (or still better, a narrow slit in a screen), when the shadow of the wire is seen magnified, with the external fringes on each side and the internal stripes within, the centre being always bright.

A tube with a narrow slit (about $\frac{1}{20}$ inch or less wide) at each end, the slits being parallel, exhibits beautiful coloured fringes, when looked through at a candle, or even at the light of the clouds.]

VIII. *Colours of Thin Plates, of Films, and of Grooved Surfaces.*—A variety of curious and brilliant optical phenomena were attributed by Newton to what he called *fits of transmission,* and *fits of reflection;* but which Dr. Young and most subsequent writers ascribe to *interference of light.* I refer now to the *phenomena of thin plates, of films, and of grooved surfaces.*

Excessively thin plates of air, liquids, or solids appear coloured when viewed by reflected and transmitted light; but the colour seen by reflection is complementary to that seen by transmission.

If the plate be of uniform thickness, the colour is uniform; but if the thickness varies, the colour also varies.

These colours succeed in a certain order or series (called Newton's scale), in the order of the thicknesses commencing from the very least thickness at which the plate does not reflect light, and when viewed in this position, appears black; but when viewed by transmitted light, appears white.

[It may be desirable here to give a table of the order of these tints, commonly called Newton's scale, as it is afterwards referred to.

1st Order - -	Black
	Blue
	White
	Yellow
	Orange
	Red.
2nd Order - -	Indigo
	Blue
	Green
	Yellow
	Orange
	Red
	Scarlet.

3rd Order	Purple Indigo Blue Green Yellow Red.
4th Order	Bluish Green Yellowish Green Red.
5th Order	Blue Red.
6th Order	Blue Red.
7th Order	Greenish Blue White.

A plate having the form of a plano-concave lens, the thinnest part of the plate being in the centre, gives a series of concentric rings of brilliant colours. Those seen by reflected light have a black spot in the centre, while the transmitted rings have a white spot in the centre, and all the colours complementary. [Such a plate of air is produced by pressing a convex lens on a plane glass: also pieces of plane glass pressed together will give various irregular bands of the same colours, according to the direction of the pressure.]

[Rings (though not exact in form) exhibiting these colours are easily formed, by pressing hard together at their centres two pieces of plate glass, at least six inches square.]

These different phenomena of thin plates are brilliantly illustrated in the lecture-room by the oxyhydrogen lime-light.

The squares of the diameters of the reflected coloured rings are as the odd numbers, 1, 3, 5, 7, 9, &c.; while the squares of the diameters of the transmitted rings are as the even numbers 0, 2, 4, 6, 8, 10, &c. Hence Newton calculated the thicknesses at which they are produced.

The brilliant colours produced by thin plates of air between the laminæ of mica, of selenite, and of Iceland spar, and between plates of glass, are familiar illustrations of the colours caused by thin plates of a gaseous substance.

The colours caused by thin films of oil of turpentine or other essential oils, of alcohol or of water, and by soap-bubbles, are well known examples of the colours caused by thin plates of liquids.

The iridescent hues produced on copper or steel by heat, and which depend on the formation of a thin film of metallic oxide, are good illustrations of the colours caused by thin plates of solids. But the most brilliant are those caused by thin films of peroxide of lead, formed upon polished steel plates, by the electrolytic decomposition of acetate of lead. These splendid tints were discovered by Nobili*, and are commonly known as *Nobili's colours* or *metallochromes*. The mode of producing them has been described by my friend Mr. Gassiot, in a paper read before the Royal Society.* If we place on the polished steel plate a card screen in which some device is cut out, very beautiful figures, having a splendid iridescent appearance, are produced.

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* See Taylor's *Scientific Memoirs*, vol. i. part 1.

In all the cases hitherto alluded to, I have supposed white or compound light to be used; and then the colours are called iridescent, but (as we have seen) not of the same kind nor in the same order as the prismatic. But if monochromatic or homogeneous light be employed, the rings are of a uniform tint or colour, and are separated by obscure bands or rings. Red light yields the broadest, violet light the narrowest rings. Hence in *white* light the superposition of these gives rise to the observed compound tints.

Minute particles, fibres, and grooved surfaces also produce iridescent colours by white light. Thus, minute particles of condensed vapour, obtained by breathing on glass, give rise to this effect. A familiar illustration is to be found in the halos observed around the street-lamps, when viewed at night through a coach-window, on the glass of which vapour is deposited. In this case the colours are seen by transmission. Dr. Joseph Reade's beautiful instrument called the *Iriscope*, brilliantly displays the colours produced by reflection from a plate covered with condensed vapour. It consists of a plate of highly polished black glass, having its surface smeared with a solution of fine soap, and subsequently dried by rubbing it clean with a piece of chamois leather. If the surface thus prepared be breathed on through a glass tube, the vapour is deposited in brilliant coloured rings. But as in this mode of experimenting, the plate of vapour is thickest in the middle and thinnest in the circumference, the rings are in the reverse order to those of Newton, having a black circumference instead of a black centre.

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* See the *Proceedings of the Royal Society*, for March, 1840; also Brande's *Manual of Chemistry*, 5th edit. p. 836.

Minute fibres of silk, wool, and of the spider's web, also present in sunshine a most vivid iridescence.

A very minutely grooved surface also presents an iridescent appearance in white light. Of this mother-of-pearl is a familiar instance. Micrometer scales frequently present the same appearances; and Barton's buttons and other iris ornaments owe their resplendence to numerous minute grooves cut in the surface of the metal. If a beam of light from the oxyhydrogen apparatus be received on one of Barton's buttons, an iridescent image may be thrown on a screen several yards distant; thus furnishing a good lecture-room illustration of the colours of grooved surfaces.

IX. *Double Refraction.*—When a pencil of light falls in certain directions on any crystals which do not belong to the cubical system, it is split or divided into two other pencils, which diverge and follow different paths; and when their divergence is considerable, objects viewed through them appear doubled. The change thus effected on a ray of light is denominated *double refraction.* The substance which is commonly used to produce this effect, is that variety of transparent crystallized carbonate of lime, called *Iceland spar,* or sometimes *calcareous spar,* or, for brevity, *calc-spar.*

In every double refracting crystal there are, however, one or more directions in which double refraction does not take place. These are called *axes of double refraction;* they might perhaps with more propriety be termed *axes of* NO *double refraction.*

I now pass a beam of light (produced by throwing the oxyhydrogen flame on lime) through a rhombohedron of Iceland spar, and we obtain two images on the screen. By rotating the crystal on its axis one of the images revolves around the other, but neither disappears during the revolution. We shall see the import of the fact in the sequel.

X. *Polarization.*—When submitted to certain influences, the rays of common light acquire peculiar properties, designated by the term *polarization.* These peculiarities are not distinguishable by the unassisted eye.

A very common question, put by persons who have not studied the subject, is, "*What is polarized light?*" and the philosopher feels very considerable difficulty in giving a concise and intelligible reply; so that the inquirer, perhaps after listening to a lengthened detail, frequently goes away, without obtaining, as he says, a direct and short answer to his question.

There are two modes of reply: *one* is to describe, independent of all hypotheses, the properties by which polarized light is distinguished from common light; the *other* is to adopt some hypothesis of the nature of light, and, therefore, to give an hypothetical explanation of the nature of polarized light. Whichever method we adopt — and I shall give both — lengthened details are necessary to enable the uninitiated to comprehend the subject.

There are four methods of polarizing light, *viz.*:—

a. Reflection.
b. Simple refraction.
c. Double refraction.
d. Transmission through a plate of tourmaline.

In the following table I have contrasted some of the distinguishing characteristics of common and polarized light:—

A Ray of Common Light,	*A Ray of Polarized Light,*
1. Is capable of *reflection*, at oblique angles of incidence, in every position of the reflector.	1. Is capable of *reflection*, at oblique angles of incidence, *in certain positions only* of the reflector.
2. Penetrates a plate of *tourmaline* (cut parallel to the axis of the crystal) in every position of the plate.	2. Penetrates a plate of *tourmaline* (cut parallel to the axis of the crystal) in certain positions of the plate, but in others is wholly intercepted.
3. Penetrates a *bundle of parallel glass plates,* in every position of the bundle.	3. Penetrates a *bundle of parallel glass plates,* in certain positions of the bundle, but not in others.
4. Suffers *double refraction* by Iceland spar, in every direction, except that of the axis of the crystal.	4. Does not suffer *double refraction* by Iceland spar, in every direction, except, that of the axis of the crystal. In certain positions, it suffers single refraction only.

Thus, then, one mode of replying to the before-mentioned question would be, by recapitulating the facts stated in this second column. This reply would form what I may term a matter of fact answer, being independent of all hypothesis.

The naked or unassisted eye cannot, then, distinguish common from polarized light. Every person must have repeatedly seen polarized light; but not knowing how to recognize it, has ailed to distinguish it from common light. If you look at a polished mahogany table, placed between you and the window, part of the light reflected from the table is polarized. When you look obliquely at the goods in a linen-draper's shop, through the plate-glass window, part of the light by which you see the articles is polarized. When you see two images by a crystal of Iceland spar the transmitted light is wholly polarized. The atmospheric light is frequently polarized, especially in the earlier and later periods of the day when the solar rays fall very obliquely on the atmosphere. At the present season (the spring), the effect may be perceived at eight or nine o'clock in the morning and five or six o'clock in the afternoon, the observer standing with his back to the sun, or with his face north or south. I have found that the effect is best perceived when the sun is shining, and the atmosphere more or less misty.

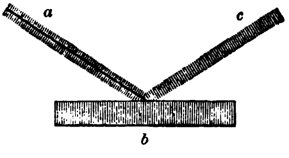
It is obvious, therefore, that after we have polarized a ray of light, we must employ some agent to detect its peculiar properties. This agent is called the *analyzer*. It might also be termed the *test*. It may be a *reflecting plate, a plate of tourmaline, a bundle of glass plates, a Nichol's prism*, or *a double refracting prism;* in fact, the analyzer or test must be a polarizer.

Thus, then, a *polariscope* consists of two parts: one for polarizing, the other for analysing or testing the light. There is no essential difference between the two parts, except what convenience or economy may lead us to adopt; and either part, therefore, may be used as polarizer or analyzer ; but whichever we use as the polarizer, the other then becomes the analyser.

a. Polarization by Reflection.—This method of polarizing light was discovered by Malus, in 1808. He was viewing, through a double refracting prism, the light of the setting sun reflected from the glass windows of the Luxembourg palace in Paris ; and, on turning round the prism, he was surprised to observe a remarkable difference in the intensity of the two images: the most refracted alternately surpassing and falling short of the least refracted in brightness.

Polarizing reflectors are usually *glass*. This should be either ground or blackened at the back to prevent posterior reflection. *Water* is seldom made use of. *Mica* may be employed instead of glass. *A well-polished* or *varnished piece of wood* (as a table, top of a

Fig. 19.



Polarization by Reflection.

a. Incident ray of common or unpolarized light.

b. Plate of glass (*polarizing plate*).

c. Reflected ray of polarized light.

pianoforte, or a counter) is very convenient. *Marble* also answers tolerably well. The *shining back of a book* is oftentimes serviceable. Metallic plates are objectionable; since by reflection from them, the light undergoes other modifications to be explained hereafter.

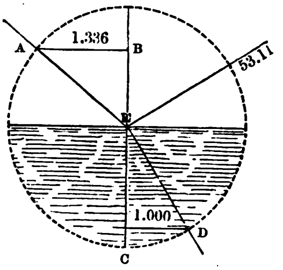
The polarizing angle varies for different substances, as the following table shows:

Angles of Polarization by Reflection.

Water	53° 11′
Glass	56° 45′
Sulphate of lime	56° 45′
Rock crystal	56° 58′
Iceland spar	58° 51′
Diamond	68° 1′

From a very extensive series of experiments, made to determine the maximum polarizing angles of various bodies, Sir D. Brewster arrived at the following law: *the index of refraction is the tangent of the angle of polarization.* It follows, therefore, as a geometrical consequence, that *the reflected polarized ray forms a right angle with the refracted ray.*

Fig. 20.



This may be illustrated as follows in (*fig.* 20.)

AB. (1·336) is the sine of the angle of incidence for water.

CD. (1·000) is the sine of the angle of refraction.

C ECD. This angle is 36·49′.

Hence 53·11′ is the maximum polarizing angle for water. For this is the complement of the angle of refraction.

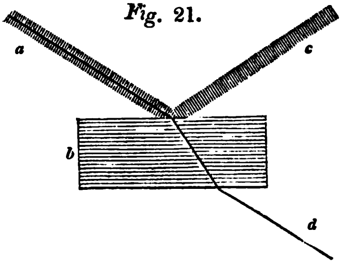
53·11′+36·49′=90°.

Here, perhaps, is the most convenient place for referring to a suggested application of polarized light. I have stated that light is polarized by water, at an angle of 52° 45′. By the analyzer as a tourmaline, or Nichol's prism (or a bundle of glass plates), the whole of this reflected polarized light may be intercepted without offering any impediment to the unpolarized but refracted light which has traversed the water; so that objects may be more readily seen at the bottom of ponds, rivers, and the sea, by this expedient than otherwise, since the glare of the reflected light is prevented. Hence anglers, and those fond of fish-spearing, may employ this property of polarized light in the discovery of the objects of their sport; and commanders of vessels may avail themselves of it to detect rocks and shoals in the bottom of the ocean, which are not otherwise visible except by viewing them from the mast-head, by which the angle of reflection is diminished, and consequently the quantity of light reflected is thereby lessened.

I proceed now to demonstrate experimentally the polarization of light by reflection, and the essential properties of the polarized ray. This is best exhibited to a class by the following method: I obtain an intense light by throwing the flame of a jet of mixed oxygen and hydrogen gases on a cylinder of lime. This light which I shall, for brevity, call the *lime-light*, is condensed by two cross lenses (called *condensers*) and thrown on a plate of glass, blackened at the back, and placed at an angle of 56° 45′. The light is polarized by this plate, and being then refracted by two plano-convex glasses (termed the *power*), is afterwards received on a semi-transparent calico screen, strained on a wooden frame, and moistened with water. A bundle of glass plates is sometimes used as a reflecting polarizer: it has the advantage of reflecting more light, but a portion of it is unpolarized.

The light thus polarized is not distinguishable by the eye from common light, but to prove its nature, I proceed to test it. For this purpose, I place a plate of tourmaline on the front of the polariscope, and on revolving it, you observe the light on the screen is alternately cut off and admitted. At 0° the tourmaline transmits the light, at 90° it absorbs it, at 180° it transmits it, at 270° it absorbs it. I remove the tourmaline, and substitute a bundle of glass plates, placed at an angle of 56° 45′. On revolving this, the light is observed to be alternately cut off and transmitted, as in the case of the tourmaline. I now substitute a double refracting prism for the bundle of glass, and on revolving this, it is seen that in two positions double refraction takes place, and two images are produced on the screen, while in two intermediate positions, one image is cut off. Thus, then, the light reflected from the blackened glass plate of the polariscope, is polarized, since it possesses the characters assigned to this kind of light.

Fig. 21.



Polarization by Single Refraction.

a. Ray of common or unpolarized light.
b. Bundle of glass plates.
c. Reflected polarized ray.
d. Refracted polarized ray. This ray is oppositely polarized to *c.*

b. Polarization by Single Refraction.—If light be transmitted obliquely through a bundle of diaphanous laminæ, it suffers polarization. The very thin parallel glass plates used for microscopes form the best medium.*

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* Sold by Bromley and Drake, at 315. Oxford Street.

Sixteen or more of these are to be placed parallel, and the bundle then placed at an angle of 56° 45′ to the ray to be polarized.

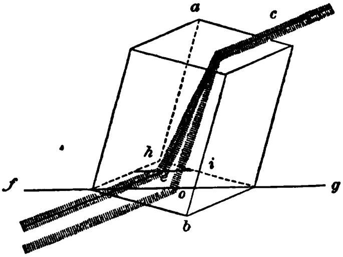
Common crown or window glass serves well enough for ordinary purposes. The flattest, thinnest, most colourless, and perfect pieces are to be selected. A very convenient mode of using them is the following:—Take two one ounce paper pill-boxes, remove the lids and the bottoms, and then paste together the two cylinders of the boxes, so as to form a tube. Into this place obliquely sixteen pieces of window glass. Having cut in each of the lids a circular hole, of about the size of a sixpence, place a lid at each end of the cylinder. The light by passing obliquely through the glass-plates in this cylinder becomes polarized.

A bundle of mica plates may be used for polarizing, but it is inferior to the bundle of microscope glass above referred to.

c. Polarization by Double Refraction. — I have already demonstrated the double refractive power of Iceland spar; though I have not hitherto said anything of the nature of the light of which the two pencils are made up.

I now proceed to demonstrate that the two pencils or rays produced by this process are polarized; but the polarized state of the one ray is of an opposite kind to that of the other; so that the two rays are said to be *oppositely polarized.* That this is the case is proved by applying our test to them. Thus if I apply a plate of tourmaline, you observe that, as this is rotated, one of the luminous rays is alternately cut off, which would not be the case were the rays composed of common light; while if both were similarly polarized, they would be simultaneously and not alternately absorbed. If I substitute the bundle of glass plates for the tourmaline, one of the rays is reflected, and the other transmitted; and by revolving the bundle

Fig. 22.



Double Refraction by a Rhombohedron of Iceland Spar.

a, *b*. The obtuse angles. A line drawn from *a* to *b* represents the axis of the crystal.

c. Incident ray of unpolarized or common light.

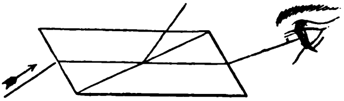
e, *o*. Oppositely polarized transmitted rays; *e* is called the extraordinary, *o* the ordinary ray.

fg. A line, which when viewed through the rhombohedron, appears doubled, *fg* and *hi*.

90°, the ray which was reflected is now transmitted, and that which was transmitted is now reflected.

Nichol's prism, or *Nichol's eye-piece**, is a most valuable and convenient polarizer or analyser. It consists essentially in a prism of calc spar so cut that a ray entering perpendicularly, or nearly so, to one face falls upon the oblique side at so small an angle that of the two rays into which it is divided, one is incident at such angle that it cannot be refracted out, but undergoes internal reflection, and is thus carried aside, while the other passes out by refraction (see *fig.* 23.).

Fig. 23.



To the oblique surface is cemented on by Canada balsam the corresponding oblique side of a similar prism of calc spar, through which the transmitted ray passes out in a direction parallel to that of incidence, and having its prismatic colour destroyed by the second prism. We thus obtain a ray wholly polarized in one plane. Over the tourmaline this prism has the advantage of being perfectly free from colour, but it has the objection of giving a very limited field of vision.

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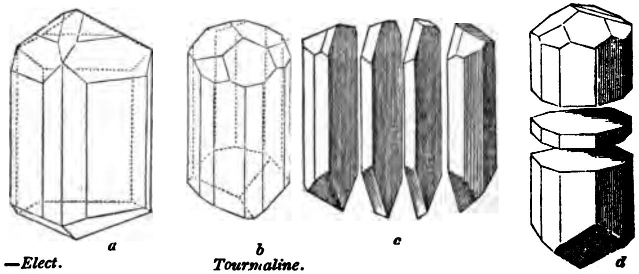
* See *Jameson's Journal*, vols. 6, 16, and 27.

d. Polarization by the Tourmaline.—The last mode of polarizing light to which I shall have occasion to allude, is by transmission through a plate of tourmaline, cut parallel to the axis of the crystal.

The substance called *tourmaline*, and to which I have already referred, is a precious stone, which is occasionally cut and polished, and worn as a jewel. There is good reason for supposing that it is the substance to which Theophrastus alludes under the name of *lyncu-*

Fig. 24.



a. Brazilian tourmaline. By cooling, the upper end becomes positively (+), the lower negatively (—) electrical.

b. Another tourmaline.

c. Tourmaline slit, parallel to the axis, into four plates, which, when ground and polished, are used as either polarizers or analyzers.

d. Tourmaline cut at right angles to its axis. The plates, thus obtained, are ground and polished, and then used in the polariscope for producing coloured rings.

rium (λυγκύριον). It is found in various parts of Europe, Asia, Africa, and America. Much of that found in commerce comes from the Brazils. It occurs in thick and short, as well as in acicular prismatic crystals, belonging to the rhombohedric system, and which have three, six, or more sides and dissimilar summits. Thus in most tourmalines the extremities or summits of the crystal differ from each other in the number or situation of the planes; and like other unsymmetrical crystals, the tourmaline becomes electrical while changing its temperature, one extremity becoming positive, the other negative.

The colour of the tourmaline is various, but green and brown are the prevailing tints. Curiously enough, there appears to be a remarkable connection between the colour and the other optical, as well as the electrical properties of the tourmaline. Green, blue, and yellow colours are, in general, imperfect polarizers. The brown and pinkish tints are the best. White colourless tourmalines do not polarize.

The principal constituents of the tourmaline are *silica* and *alumina*. *Boracic acid* is always present, as also *magnesia*. *Iron*, *potash*, *soda*, *&c.*, are not constant ingredients.

For optical purposes, the tourmaline is cut in two directions, viz. *parallel*, and likewise at *right angles to the crystallographical axis.* Tourmaline plates for *polarizing or analyzing*, are cut parallel to the axis about $\frac{1}{20}$ of an inch thick; but for depolarizing, a process to be hereafter explained, or showing coloured rings, *at right angles to the axis.* Considerable care and experience are required to prepare good plates.* If they be not cut perfectly parallel to the axis, their polarizing and analyzing powers are greatly impaired. In buying plates, avoid cracks, flaws, and deep colours, and select those which by experiment you find to be good polarizers, for as the polarizing powers are very unequal in different crystals, nothing but a trial of each plate can determine its goodness.

The light which is transmitted by a plate of tourmaline (*a* or *a′*) (cut parallel to the axis), is plane-polarized. A second plate of tourmaline (*b*), if held in the same position, transmits the light polarized by the first plate; but if the second plate (*b′*) be turned round, so that its axis is at right angles with the axis of the first plate, no light is transmitted.

The great objection to the tourmaline, as a polarizer, is, that the transmitted polarized beam is more or less coloured, and also that a large proportion of light is lost. If large, transparent, and colourless polarizing tourmalines could be obtained, they would be invaluable to the optician.

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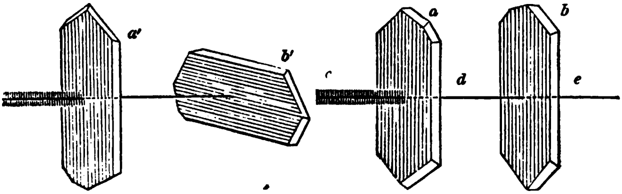
* Mr. Darker, of Paradise Street, Lambeth, prepares tourmaline plates for most of the opticians.

That common light is polarized by transmission through a plate of tourmaline, as above described, is proved thus: — A second tourmaline, placed with its axis at right angles to the first, does not permit light to pass. But when the axes of the plates coincide, the light polarized by the first plate is transmitted by the second. Moreover, if the light transmitted through the first tourmaline be received at an

Fig. 25.



Action of Tourmaline Plates on Light.

a, *b*. Two plates of tourmaline (cut parallel to the axis of the crystal), with their axes coincident; *a*, is called the polarizer, and *b*, the analyzer.

c. Incident ray of unpolarized light.

d. Transmitted ray of light polarized by *a*.

e. Ray polarized by *a*, and transmitted by *b*.

a′, *b′*. Two plates of tourmaline with their axes opposed, so that the light, polarized by *a′*, is intercepted by *b′*.

oblique angle on a plate of glass, blackened at the back, it is reflected only on two sides of the ray, and at an angle of 56° 45′. Lastly, if it be tested by a double refracting prism, it is found to produce double refractions in two positions only of the ray, for on rotating the double refracting prism on its axis, we find that one of the images is alternately cut off, and in intermediate positions, two faint images only are produced.

XI. *Wave Hypothesis of Light.* — There are two hypotheses or theories which have been formed to account for the phenomena of light; one of these is called the *projectile theory*, or the *theory of emission;* — while the second is denominated the *wave*, or *undulatory theory of light.*

The first is sometimes called the *material* or *Newtonian theory* of light. But as on both hypotheses a fine subtile form of matter is required to account for luminous phenomena, the one hypothesis equally deserves the name of *material* with the other. Moreover, I cannot understand why the projectile theory is to be exclusively honoured with the name of the *Newtonian;* for though on some occasions Newton certainly adopts it, yet on others he appears to support the theory of waves.

On the present occasion it is not my intention to enter into any details respecting the projectile theory; for however ably and plausibly it accounts for some optical phenomena, it is manifestly incompetent to explain those which it is the object of this course of lectures to describe.

Light, a Property or Motion. — The wave theory supposes that light is a *property* — a *motion* — a *vibration* of something. But of what? Euler imagined that the vibrating medium, in dense bodies, was the body itself; through the gross particles of which he supposed the light to be propagated in the same manner as sound. The hypothesis, Dr. Young * declares to be "liable to strong objections;" and he adds, that, "on this supposition, the refraction of the rays of light, on entering the atmosphere from the pure ether which he describes, ought to be a million times greater than it is."

Ether. — To account for the phenomena of light, philosophers have assumed the existence of a vibrating medium, which has been called *the ethereal medium*, the *luminiferous ether*, or simply *ether*. It is supposed to be a rare, highly *elastic* †, subtile fluid, which occupies all space and pervades all bodies. As the sensation of light is supposed to be excited by the undulations of this medium, so, where light exists, there ether must be. Hence it fills all space. It is between the sun and the earth, the earth and the stars, and so on. If it did not exist in water, diamonds, glass, &c., these bodies would not be diaphanous. So that it must pervade all bodies. Even opaque substances must contain it, since, as in the case of gold, these become transparent when excessively thin.*

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* *A Course of Lectures on Natural Philosophy*, vol. ii., p. 542. Also *Phil. Trans.* for 1800.

† *Elasticity of the Ether.*—"In the interior of refracting media the ether exists in a state of less elasticity, compared with its density, than in vacuo; and the more

Existence of an Ether. — We have no independent evidence to adduce of the existence of this medium. It is, therefore, an assumption; but one which is sanctioned by the high authority of Descartes, Huyghens, Euler, Hooke, Newton, Young, Fresnel, and some of the most distinguished philosophers of the present day, among whom are Sir J. Herschel and Arago. These eminent men have seen in this assumption nothing inconsistent with their knowledge

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refractive the medium the less, relatively speaking, is the elasticity of the ether in its interior." (*Herschel*, 563.).

* "In the explanation of the law of refraction, the *undulatory hypothesis* requires that the velocity of the light should be less in the denser medium than in the rarer; while, in the *material system*, the contrary must be the case. Could this fact be submitted to experiment, we should immediately be enabled to decide the question." (Lloyd, *Lectures on Light and Vision*, p. vi. 1831.)

of the constitution of the universe. The electrician and the magnetician have assumed, respectively, an electric and a magnetic fluid, and there can be no impropriety, therefore, in the optician assuming a luminiferous ether, provided, however, that it be compatible with well ascertained facts, and do not violate known laws. Moreover, it is by no means improbable that the fluids which have been respectively assumed as the causes of electrical, magnetical, calorific, and luminous phenomena, may be one and the same. It has seemed to some a possible conjecture that even gravity, perhaps, may be referable to the same cause. Newton* himself has thrown out a speculation of this kind. Alluding to the ether, he says, "Is not this medium much rarer within the dense bodies of the sun, stars, planets, and comets, than in the empty celestial spaces between them? And in passing from them to great distances doth it not grow denser and denser perpetually, and thereby cause the gravity of those great bodies towards one another, and of their parts towards the bodies; every body endeavouring to go from the denser parts of the medium towards the rarer?" Very recently, Dr. Roget † and

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* *Opticks*, p. 325. Query 21.

† *Electricity*. Published in the *Library of Useful Knowledge*.

Mosotti[*] have shown how, on the assumption of an ethereal medium, the phenomena of gravitation and electricity may be included in the same law.

It has been said, that if the universe contained a fluid of the kind here referred to, the planets must experience some resistance to their motions, and, therefore, that as no resistance can be detected, there can be no ethereal medium. This conclusion, however, is by no means a necessary one, for "if this ether," says Newton[†], "should be supposed 700,000 times more elastic than our air, and above 700,000 times more rare, its resistance would be above 600,000,000 times less than that of water. And so small a resistance would scarce make any sensible alteration in the motions of the planets in ten thousand years." The most satisfactory evidence of this resistance, if indeed it exist, might be expected to be found in the case of the comets, bodies made up of the lightest materials, in fact, masses of vapour, and, therefore, from their less momentum, more likely to suffer retardation. In the case of Encke's comet, evidence of this resistance is believed to have been obtained. The mean duration of one entire revolution of this comet is about 1207 days, and the "magnitude of the resistance is such as to diminish the periodic time about $\frac{1}{10000}$ of the whole at each revolution; a quantity so large that there can be no mistake about its existence."*

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[*] *On the Forces which regulate the Internal Constitution of Bodies*, in Taylor's *Scientific Memoirs*, part iii.

[†] *Opticks*, p. 327. Query 22.

The following table of the mean duration of one entire revolution of this comet, allowance being made for perturbations occasioned by the action of neighbouring planets, is taken from a memoir by Encke.†

	Days.
From 1786 to 1795..............	1208·112
" 1795 to 1805..............	1207·879
" 1805 to 1819..............	1207·424

Sir John Herschel ‡ observes, that "on comparing the intervals between the successive perihelion passages of this comet, after allowing, in the most careful and exact manner, for all the disturbances due to the actions of the planets, a very singular fact has come to light, viz., that the periods are continually diminishing, or, in other words, the mean distance from the sun, or the major axis of the ellipse, dwindling by slow but regular degrees. This is evidently the effect which would be produced by a resistance experienced by the comet from a very rare ethereal medium pervading the regions in which it moves, for such resistance, by diminishing its actual velocity, would diminish also its centrifugal force, and thus give the sun more power over it to draw it nearer. Accordingly (no other mode of accounting for the phenomenon in question appearing), this is the solution proposed by Encke, and generally received. It will, therefore, probably fall ultimately into the sun, should it not first be dissipated altogether, a thing no way improbable, when the lightness of its materials is considered, and which seems authorised by the observed fact of its having been less and less conspicuous at each reappearance."

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* Airy, *Report on the Progress of Astronomy, in the Report of the British Association for* 1833.

† *Astronomische Nachrichten*, Nos. 210, 211.

‡ *Treatise on Astronomy* (in *Lardner's Cyclopædia*), p 309.

So extensive a theory as that of undulations of course must have its difficulties and be open to many objections.

"One of the principal objections urged against the *undulatory hypothesis* is that, according to it, light should not only be propagated in right lines, but in every direction, as is the case with sound; so that there could be no shadow, no absence of light produced by the intervention of an obstacle. To this the supporters of the system reply, that this lateral propagation of the pulses of an elastic medium is less, the greater the velocity of the pulses, as that of sound is less than that of water, &c.: so that they consider themselves justified in inferring, that when the velocity of propagation is so great as that of light, the lateral propagation must be insensible."*

Moreover, on the principle called "the mutual destruction of secondary waves," it has been proved that such lateral spreading of waves must in a great degree destroy itself. But also in point of fact, it does to a certain degree exist.

Sir D. Brewster † states, that there are certain classes of facts which the wave theory will not explain. Two of these only he mentions:

1st. The phenomena of *transverse fringes* which cross the fringes produced by grooved surfaces and produce, both in common and homogeneous light, a series of phenomena equally beautiful and singular. In these phenomena we witness the extraordinary fact that a stripe of polished metal is incapable, at various angles of incidence, of reflecting a single ray of homogeneous light; while at intermediate angles of incidence, it reflects that light freely.

2. The second group of phenomena present themselves in looking at a perfect solar spectrum,

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* *Lloyd on Light and Vision*, p. 6.

† *Athenæum*, July 12. 1845.

or a diffractive spectrum, through the edge of a thin plate of glass, quartz, or mica. If we cover one half of the pupil of the eye with such a plate, and with this view the spectrum so that the rays which pass by the edge of the plate may interfere with those which pass through it, then if the plate is seen in the same side as the *violet space,* the spectrum is seen crossed with numerous black and nearly equidistant bonds parallel to Frauenhofer's fixed lines, and generally speaking increasing with the thickness of the plate; but if the plate is on the same side as the *red space,* no bonds whatever are seen, though all the other conditions of their production are the same. This he called a *new polarity.*

In reply to Brewster, Airy and others expressed themselves to the effect that they did not doubt of the capability of the theory to explain the phenomena, however complicated. Airy indeed has done so with respect to the "new polarity," though Brewster at first denied its accuracy [yet the subsequent investigation of Mr. Airy completely settled the question.* There are, however, many phenomena which as yet remain unexplained by the undulatory theory, chiefly such as would require such an extension of the analytical formulas as the state of the calculus does not at present enable us to pursue].*

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* See *Phil. Mag.*, November and December, 1846.

Leaving these speculations, I proceed to point out the properties which an ethereal medium must be supposed to possess.

Ethereal Molecules. — The ether consists, or is made up of minute parts, which we call *molecules*, between which there must exist attractive and repulsive forces †, in virtue of which the ether possesses extreme elasticity. Moreover, there appears to exist some attractive force between the ethereal molecules and the particles of the grosser forms of matter. Indeed, Dr. Young supposed that the vibrating medium is the ether and ponderable matter conjointly.

But instead of insisting on the actual existence of an ethereal medium composed of molecules, we " may be content to look at the theory simply as a mathematical system, which faithfully represents, at least, a wide range of phenomena, and to some extent connects the laws so made out with dynamical principles regulating the motions of a system of points, combined to form an elastic system, which, for *brevity* and *illustration, we call molecules,* constituting an *ethereal medium.*"*

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* *Phil. Mag.*, July, 1852.

† See a paper by Mr. Earnshaw, *On the Nature of the Molecular Forces which regulate the Constitution of the Luminiferous Ether*, in the *Transactions of the Cambridge Philosophical Society*, vol. vii., part 1.

Ethereal Waves. — If we suppose the existence of attractive and repulsive forces between the ethereal molecules, it follows, that when these molecules are at rest or have attained a state of equilibrium, any attempt to move one molecule must be attended with the displacement of several; for the motion is extended to adjacent molecules. So that if a vibratory movement be communicated to one, it is extended to several. If the constituent particles of a body be disturbed by any cause whatever, (provided they have not been carried beyond the limits within which the stability of the equilibrium is confined), will return again to a state of repose. This is effected by the particles alternately approaching the position of rest and receding from it, until, after some time, equilibrium is restored. The movements thus generated are termed *vibrations,* or *oscillations.* Now, an assemblage of vibrating molecules successively, in all phases of vibration, constitutes an *ethereal wave.* These vibrations being communicated through successive portions of the ethereal medium reach the retina or expanded optic nerve, and are propagated along the optic nerve to the brain, where they excite in us the *sensation of light,* just as the vibrations of the air communicated to the auditory nerve, and from thence to the brain, produce the sensation of sound.

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* *A General and Elementary View of the Undulatory Theory, as applied to the Dispersion of Light.* By the Rev. Baden Powell, 1841, pp. 4 and 5.

The number of impulses made by the ethereal molecules on the retina in a given time, determines the *colour of the light,* just as the number of impulses by the aerial molecules on the auditory nerves determines the *pitch, note,* or *tone* of sound. Hence colours are to the eye what tones are to the ear.

Undulations of Elastic Fluids. — All elastic fluids are susceptible of undulatory movements, if the equilibrium of their particles be disturbed by any cause whatever. Their oscillations are in the main similar to those of non-elastic fluids, modified, however, by the extreme compressibility and expansibility of their constitution.

If a vibration be imparted to the air at any point whatever, it will be communicated to the surrounded particles, which will recede, in consequence of the facility with which they move among each other, with equal velocity in all directions, driving before them all those particles which lie in their path. Each of these, because of its inertia, opposes a certain resistance to this movement; and the air, by virtue of its compressibility, becomes condensed; consequently the movement of the particle originally excited will be communicated through the mass.

" From Newton's measures of the thicknesses reflecting the different colours, the breadth and duration of their respective undulations may be very accurately determined. The whole visible spectrum appears to be comprised within the ratio of three to five, which is that of a major sixth in music; and the undulations of red, yellow, and blue, to be related in magnitude as the numbers 8, 7, and 6; so that the interval from red to blue is a fourth. The absolute frequency expressed in numbers is too great to be distinctly conceived, but it may be better imagined by a comparison with sound. If a chord sounding the tenor $\overline{\mathrm{C}}$, could be continually bisected forty times, and should then vibrate, it would afford a yellow green light: this being denoted by $\overset{41}{\mathrm{C}}$, the extreme red would be $\overset{40}{\mathrm{C}}$, and the blue $\overset{41}{\mathrm{D}}$. The absolute length and frequency of each vibration is expressed in the table;"* supposing light to travel at the rate of 192,000 miles per second.

COLOURS.	Length of an Undulation in parts of an Inch in Air.	Number of Undulations in an Inch.	Number of Undulations in a Second.
Extreme	·0000266	37640	458 millions of millions.
Red..................	·0000256	39180	477 "
Intermediate	·0000246	40720	495 "
Orange	·0000240	41610	506 "
Intermediate	·0000235	42510	517 "
Yellow	·0000227	44000	535 "
Intermediate	·0000219	45600	555 "
Green........................	·0000211	47460	577 "
Intermediate	·0000203	49320	600 "
Blue	·0000196	51110	622 "
Intermediate	·0000189	52910	644 "
Indigo........................	·0000185	54070	658 "
Intermediate	·0000181	55240	672 "
Violet........................	·0000174	57490	699 "
Extreme	·0000167	59750	727 "
Mean of all, or white	·0000225	44440	541 "

Lengths of ethereal Waves.—The particles of ether must be subject to infinitely varied forces; and, therefore, the waves or undulations must be infinitely varied in length.

All waves between 0·0000266 of an inch and 0·0000167 of an inch produce impressions of light or are *colorific*,—the first giving rise to the extreme red, the second the extreme violet. These only are capable of exciting vibrations in the optic nerve capable of producing vision.

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* Dr. Young's *Course of Lectures on Natural Philosophy*, vol. ii. p. 627. The above table is also taken from this work. Dr. Young calculated the velocity of light at 500,000 million feet in 8⅛ minutes; but I have adopted Sir John Herschel's assumption of 192,000 miles per second, which makes the numbers in the fourth column of the table different to those given by Young.

No other waves produce an impression on the eye: but such may be sensible to us by their heating or chemical effects: we may call them *calorific* and *chemical waves.* But in the solar beam there is no evidence of their being distinct from the luminiferous waves.

The maximum of *calorific* effect is situated at the red end of the spectrum; the *chemical* beyond the violet end.*

Amplitude of Vibrations (*Intensity of Light*). —The amplitude of vibration is the maximum excursion from rest of each molecule of the ether.

The *intensity* of the light depends on the amplitude of the vibrations: just as the intensity of the sound yielded by a vibrating cord depends on the amplitude of the oscillations.

If in the same medium, the amplitude of the oscillation is doubled, the absolute velocity will also be doubled, and the living force, or the intensity of the light, will be quadrupled.†

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* On this subject see Fresnel, p. 127.

† Ibid., p. 121.

The following synoptical table will place in one view the chief points of the wave theory.

Wave or undulatory Hypothesis.

1. Sensation of light produced by agitation of retina.
    - *a.* Agitation caused by vibrations of ether.
    - *b.* Intensity depends on the amplitude of the vibrations.
    - *c.* Colour on the number of waves in a given time.
2. Ether; its existence assumed.
    - *a.* Pervades transparent bodies and universal space.
    - *b.* Is highly elastic.
        - Elasticity less in refractive media.
    - *c.* Composed of vibratile molecules.
3. Ethereal Molecules.
    - *a.* Attractive and repulsive forces of.
    - *b.* Transversal vibrations of.

α. Rectilinear	in all azimuths	(*common light*).
	in one azimuth	(*polarized light*).
β. Curvilinear (right or left)	elliptical	
	circular	

- *c.* Amplitude of vibrations (*intensity of light*).
- *d.* Velocity,
    - Varies according to the amplitude of the vibration

4. Ethereal waves or undulations.
    - *a.* Varieties.

1. Plane	in all planes	(*common light*).
	in one plane	(*polarized light*).
2. Helicoidal	elliptical......	
	circular	

- *b.* Lengths,
    - 1. Of visible (colorific) waves.
        - *α.* 0·0000266 of an inch (*extreme red*).
        - *β.* 0·0000167 of an inch (*extreme violet*).
    - 2. Of invisible (calorific or chemical) waves.

- *c*. Heights (*intensity*).
- *d*. Velocity of propagation (*velocity of light*).
  - α. Independent of height.
  - β. Affected by the medium (*refraction*).
    - Less in refractive media.
  - γ. Affected by the length of the wave (*dispersion*).
    - Less for shorter (*violet*) waves.
    - Greater for longer (*red*) waves.
- *e*. Number of colorific waves in a second.
  - α. 458 billions (*extreme red*).
  - β. 727 billions (*extreme violet*).
- *f*. Interferences.

- 1\. Of common light.
  - α. Similar and equal waves.
    - 1\. Difference an even number of semi waves (*complete accordance*).
    - 2\. Difference an odd number of semi waves (*complete discordance*).
    - 3\. Difference intermediate (*partial discordance*).
  - β. Similar but unequal waves.
  - γ. Dissimilar waves.

- 2\. Of plane polarized light.
  - α. Waves polarized in same plane }
  - β. Waves polarized in inclined planes } (*fringes*).
  - γ. Waves polarized in rectangular planes (*no fringes*).
    - 1\. Difference any number of semi waves (*plane*).
    - 2\. Difference an odd number of quarter waves (*circular*).
    - 3\. Difference a fractional number of quarter waves (*elliptical*).

There is a *limit to the sensibility of both ear* and *eye,* that is, a certain number of impulses must be made in a given time on these organs before we become sensible of them; and if we go on augmenting the number, we cease to be sensible of them after a certain time. Now, the limits of sensibility of the eye are much more confined than those of the ear; or, in other words, the sensibility ceases much sooner in the case of the eye than in that of the ear.

The following is the range of the human hearing according to Biot[*]:—

	Number of Vibrations in one Second.	Length of Sonorous Waves.	
		Feet	in.
Commencement of appreciable sounds......	32	32	0
	64	16	0
	128	8	0
	256	4	0
	512	2	0
	1024	1	0
	2048	0	6
	4096	0	3
End of appreciable sounds.........................	8192	0	1⅛

But the actual range varies in different individuals, and we shall not be far from the truth if we assume, with Dr. Wollaston[†] and Sir John Herschel[‡], that the whole range of human hearing includes about nine octaves.

[*] *Précis Elémentaire de Physique*, vol. i. p. 324.

[†] *Phil. Trans.* 1820, p. 306.

[‡] *Encyclopædia Metropolitana*, art. *Sound*, p. 792.

Now, on comparing the range of human hearing with that of vision, we find the relative limits of the two senses to be as follows:—

	Eye.	Ear.
Commencement of sensibility	1	1
Cessation of ditto	$1\frac{58}{100}$	1024

It is highly probable, however, that the range of human vision, like that of hearing, is subject to variation in different individuals.

From these observations, then, it will be understood, that, according to the undulatory theory, the *colour* of the light depends on the lengths of the waves, or on their number in a given time. Thus *red* has the largest waves, and, therefore, the smallest number in a given time; while *violet* has the shortest waves, and, therefore, the greatest number in a given time.

The *intensity* of the light depends on the amplitude or extent of excursion of the ethereal molecules from their points of rest; or, in other words, on the height of the wave. Just as when we make a cord sound, we find that the sound diminishes in proportion to the diminution of the amplitude of the oscillations.

Velocity of the Propagation of the Undulations.—When we speak of the velocity of light, we always speak of the velocity of its propagation: this must not be confounded with the absolute velocity of the ethereal molecules, in their *vibrations.*

The velocity of the propagation is the promptitude with which the motion is communicated from one stratum to another: it is independent of the intensity of the vibrations. Thus the slightest light is propagated with the same intensity as the brightest (*Fresnel*).

The velocity is affected by the medium in which the light is propagated. In some bodies the elasticity of the ether is less, and consequently the velocity is also less. This difference is in fact the cause of *refraction* (*Herschel*).

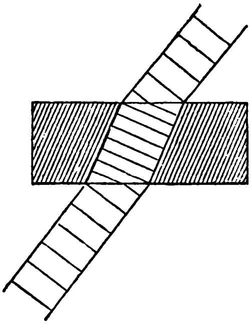
The length of the wave affects the velocity. Mathematicians long held that the propagation was the same for all lengths. But observation has proved that different colours are differently refracted: M. Cauchy has, however, removed the difficulty; and it is now admitted that the velocity of propagation varies with the length of the wave; being less for the shorter waves, greater for the longer waves.

[This is, in fact, a subject of great interest as well as difficulty. In a word, according to the earlier views of the undulatory theory, light of all colours ought to be equally refracted, which we know it is not. M. Cauchy, by taking a slightly different view, while he includes the explanation of other phenomena, just as in the previously received view of the theory, makes it also extend to this case, and shows that in general light of different colours (*i. e.* wave lengths) *ought* to be unequally refracted, as in fact it is. When we come to *numerical* results, this is found to apply exactly to all media in which accurate observations have been made of *moderate* dispersive power. But when we advance to those of *very high* dispersive power, there are considerable discrepancies from theory. It has been shown, however, that an *empirical* alteration of the formula will include these cases, while it applies equally well to the others. But this *empirical* alteration is not justified by theory.

This may be considered as the exact present state of the investigation. For particulars the reader is referred to Prof. Powell's treatise on the Undulatory Theory, &c., before mentioned.]

[The mode in which the refraction takes place, and the contraction of the waves on entering a denser medium, may be illustrated by the annexed diagram (*fig.* 26.). For experimental proof that the wave lengths are *contracted* in the denser medium, see Phil. Mag., Dec. 1832.]

Fig. 26



The nature of vibrations generally, as exhibited by a stretched cord, may be considered as threefold:—

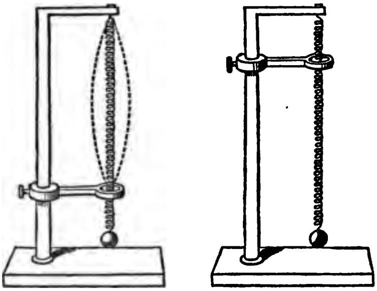
1. Transversal, or when each particle moves in a direction at right angles to the length of the string.

2. Longitudinal, or when the motion is by expansion and contraction along the length of the string.

3. Rotatory, or around the axis in a spiral form.

These varieties are well illustrated by Prof. August's apparatus, the principle of which is represented in the annexed sketch. It consists

Fig. 27.



of a weight which stretches a spiral wire, which is confined at any one point by a ring capable of being adjusted to any height.

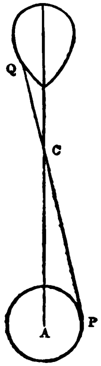
1. If the wire be at its full length, on pulling it in the middle, it vibrates *transversely.*

2. Raising the ring, raise and then let go the weight, and the wire vibrates *longitudinally.*

3. Twist the wire and then allow the weight suddenly to fall, and we get the rotatory or spiral vibration.

If a series of bodies or molecules be each in a state of vibration, and each at the same instant be in a different stage, or phase, of its vibration, and this in a regular order of succession, so that at the same instant the first molecule is at the commencement of its vibration, the next a little advanced, the third still more, &c., &c., the assemblage of these motions constitutes a wave. Each molecule performs its own vibrations in its own path, from which it does not deviate; but the *wave moves on,* or the form assumed by the configuration of the molecules at each moment passes on to the next set, and so on. To illustrate at once the performance of these *vibrations* of several different kinds, and the resulting *propagation of waves* of corresponding kinds, Prof. Powell has contrived a machine as follows. It is founded upon this geometrical construction: a finite line, P Q, moves always through the point C, and with its end P always in the circumference of a given circle, whose centre is A; the end Q will describe a certain curve, which appears upon analysis to be one of a high order, but having *in general* some sort of oval form, which varies as the distance A C is altered. If A C be very great compared with the radius of the circle, Q will move up and down, *almost* in a straight line: if A C be somewhat less, its path will *resemble* an ellipse; if still less, it will be more rounded or *resemble* a circle.

Fig. 28.

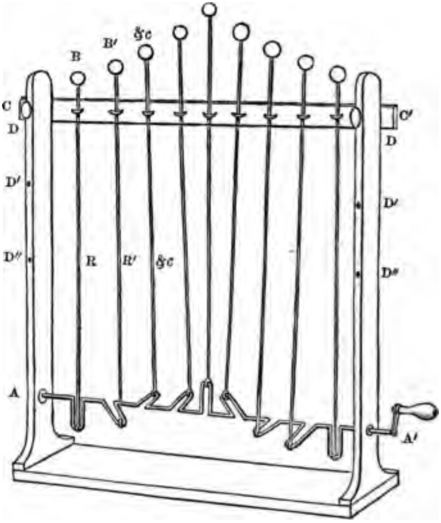


Upon this the machine is constructed as follows (A and C correspond in both diagrams):—

The lower part consists of a stout iron wire bent into a series of cranks, of which the two extremes are in the same position, *e. g.* downwards; the middle one vertical, and the intermediate ones at intermediate inclinations. Attached to each crank by a hinge or joint, is a long rod, R R′, *&c.*, which passes through an aperture in a cross-bar, C C′, at the top. The top of this rod is made conspicuous by an ivory ball or a ball painted white, B, the rest of the apparatus being painted black. The bar C C′

is attached to the supports A C A′ C′, by screws, and can be removed (without changing the rods)

Fig. 29.



from D D to the positions D′ D′, or D″ D″. The proportions of the machine are not essential, but only that the lengths of the rods should be great compared with that of the cranks. When the bar is at D D, on turning the handle, a plane polarized wave is produced by the balls; when at D′ D′ an elliptical one; and when at D″ D″ a circular one — that is, what, for illustration, and to the eye, may be considered so. If the distance A D″ be eighteen inches, A D′ should be about twenty-four, and A D about thirty-six inches; but these are not material as to exactness. *Fig.* 29. represents this machine in its original *simple* and effective form.*

Transversal Vibrations.—I come now to a most important part of the undulatory hypothesis—that by which the phenomena of polarized, as distinguished from those of common or unpolarized, light are accounted for. I refer now *to the hypothesis of transversal vibrations,* first suggested, I believe, by Dr. Young, but most admirably developed and applied by Fresnel.

"The existence of an *alternating motion of some kind,* at minute intervals along a ray, is," says Prof. Powell†, "as real as the motion of translation by which light is propagated through space. Both must essentially be combined in any correct conception we form of light. That this alternating motion must have reference to certain directions *transverse* to that of the ray is equally established as a consequence of phenomena, and these two principles must form the basis of any explanation which can be attempted."

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* [Some attempts at improvement on it profess to dispense with the cranks: but if there were not *really* a crank, or what is equivalent to it, the essential principle of the instrument would be lost, as the balls could not revolve in oval curves.]

† *A General and Elementary View of the Undulatory Theory,* p. 4.

In order to understand transversal vibrations, let us first consider how waves of water, and of other liquids, are formed. If a stone be thrown into a pond, there is formed a system or group of waves, which commences at the spot where the stone impinges, and gradually extends outwards in the form of concentric circles.* The aqueous particles in the centre are forced down, and the surrounding ones thereby urged upwards above the normal level of the water. In this way the central depression, and the first or innermost circular heap, are formed. But gravity soon causes this heap to subside, and fill up the central depression, while by its downward progress it acquires momentum, and thereby descends below its normal level, thus not only giving rise to a circular depression,

* "Self-love but stirs the virtuous mind to wake,
As the small pebble stirs the peaceful lake;
The centre moved, a circle straight succeeds;
Another still, and still another spreads."

Pope's "*Essay on Man*," quoted by Browne, vol. iii. pp. 228-9.

but causing the formation of another and outer circular heap by the elevation of the neighbouring particles. In this way the waves gradually extend outwards. It is obvious, then, that in *waves of liquids*, the directions of vibration of the molecules is *vertical*, or nearly so, while the propagation of the waves is *horizontal.*

In a vibrating cord, *the vibrations are rectangular to the propagation of the undulations* along the cord.

In *luminous waves*, the direction of vibration is supposed by Fresnel to be *transverse* to the direction of propagation. "If the particles of the ether be supposed to vibrate in the direction of the ray itself, it seems inconceivable that such a ray could bear a different relation to the different parts of the surrounding space; everything, in fact, would be similar on all sides of the ray — above and below, on the right hand and on the left."* The researches of Cauchy establish the doctrine of transversal vibrations; his general theory, indeed, includes mathematically a third vibration, namely, one *parallel* to the ray, or makes the motions of the molecules take place in *three rectangular axes.* This third vibration, parallel to the ray, seems to have no representative in nature.

Now, *polarized light*, on the wave hypothesis, is light which has only one *plane* or azimuth of vibration; whereas *common* or *unpolarized light* consists of light having *two or more planes* of vibrations, all azimuths, of which two must be rectangular — that is, after the molecules have vibrated in one *plane* or azimuth, they change their vibration to another *plane* or azimuth. So that common light consists in a rapid succession of waves in which the vibrations take place in different planes. It does not, however, appear that the planes of vibration are *continually* changing; but that in each system of waves, there are probably several hundred successive vibrations, which are all performed in the same plane; although the vibrations of one system bear no relation to those of another. Thus, then, we call that light *polarized*, in which all the vibrations take place in *one* plane; but when vibrations are succeeded rapidly by other vibrations in an opposite plane, the two waves, though *separately* called *polarized*, are, *together*, termed *unpolarized* or *common* light; so that, as Fresnel has observed, *common* light is merely *polarized light, having two planes of polarization at right angles to each other.*

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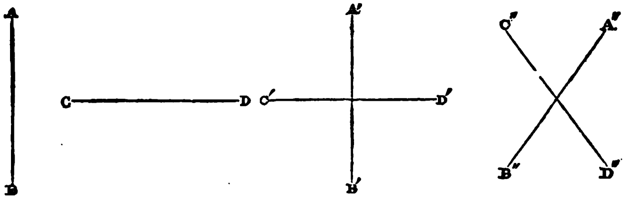
* *Lloyd's Lectures*, p. 25.

Thus, then, I have now replied theoretically, as well as practically, to the question, "*What is polarized light?*"

Partially polarized light consists, according to Sir John Herschel, of two unequally intense portions; one completely polarized, the other not at all. Sir David Brewster, however, regards it as light whose planes of polarization are inclined at angles less than 90°. But to the latter view some objections have been raised by Mr. Lloyd.

In the following diagram, let the straight lines represent the directions in which the ethereal molecules are supposed to vibrate. Then A B and C D will represent the direction of vibration of the ethereal molecules of two oppositely polarized rays: A B′ C′ D′ the two rectangular directions of vibration of a ray of common or unpolarized light; and A″ B″ C″ D″ a ray of partially polarized light, according to Sir D. Brewster's hypothesis.

Fig. 30.

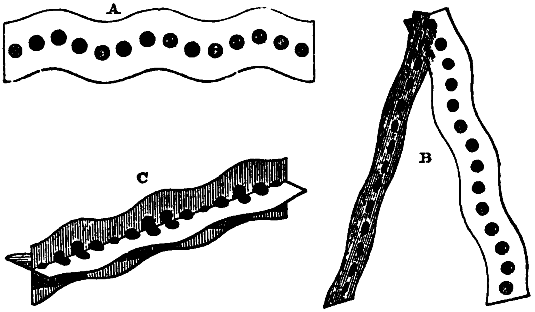


"The difference between a polarized and an ordinary ray of light," says Sir John Herschel, "can hardly be more readily conceived than by assimilating the latter to a cylindrical, and the former to a four-sided prismatic rod, such as a lath or a ruler, or other long, flat, straight stick."

In order to illustrate Fresnel's notion of transversal vibrations, and of the hypothetical difference between common and polarized light, *painted card models* are very convenient. A piece of card-board is cut out in a waved or undulated form, so that the curves of the upper and lower edges accord. Then, midway between these edges, a row of circular black spots is painted on the card: these are to represent the ethereal molecules, while the card-board represents the plane of vibration. A single card thus cut and painted serves to illustrate a ray of plane-polarized light (*fig.* 31. A): two of them placed side by side, with their planes at right angles to each other, B, represent the two oppositely-polarized rays produced by a double refracting prism, while two so placed that they mutually cross represent common light, C.

We are now prepared to understand how common light becomes polarized. In the case of the *doubly refracting bodies* the two planes separate, for reasons that will be explained in the next lecture; and as the two waves have the planes of their vibrations at right angles to each other, we see now how the rays are said to be oppositely polarized. As these two waves are propagated with different velocities, they in consequence follow different paths.

Fig. 31.



The *tourmaline* likewise separates the two planes; but it gradually extinguishes the one, by offering such an impediment to its progress that its vibrations are destroyed. The agency of the *reflecting plate* in polarizing light may also be readily accounted for. When a ray of common light falls on a transparent surface, at a certain angle, its planes of vibration are resolved into two, one of which is transmitted, the other reflected; both are polarized, but oppositely.

The action of the *analyzer* or *test* may also be easily understood. Suppose the analyzer to be a *reflecting plate:* if this plate be at the same angle to the ray as the polarizing plate, the vibrations will be reflected when the planes of reflexion of the polarizing and analyzing plates coincide — but will be transmitted (that is, not reflected) when the planes are at right angles to each other. Suppose the analyzer to be a *tourmaline* plate: in one position this plate permits the vibrations to be transmitted, but in a position perpendicular to this it destroys them. So that in these two rectangular directions the crystal of tourmaline must possess unequal elasticities; for the motion or vibration is transmitted in the one, but stifled or destroyed in the other direction. Suppose the analyzer to be a *rhombohedron of Iceland spar;* in either of two rectangular directions the vibrations of the polarized incident ray are propagated unchanged, but at an angle of 45° to either of these positions, the plane of vibration of the incident ray is resolved into two rectangular planes, each of which forms an angle of 45° with the incident ray.

Interferences of Light. — It is a law in dynamics, that the velocity produced by two joint forces, when they act in the same direction, will be as the sum of the forces. Hence if two waves, all of whose parts respectively coincide, meet, it is evident that their velocities will be doubled. Whether the vibrating medium be

[illegible] of [illegible] particles not–
[illegible]

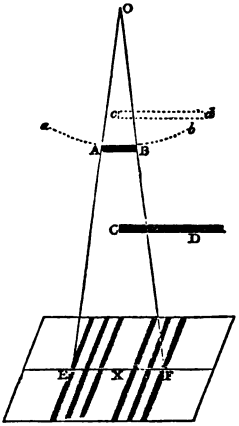
water, or air giving rise to *sound,* or ether giving *light,* this statement holds good: the intensity of the waves is doubled.

But the velocity of two joint forces, when they act in opposite directions, will be as their differences. Hence, if a wave (of water, air, or ether) be half an undulation behind another wave, the velocities of the two are mutually destroyed. If two elevations meet in exactly opposite directions, an elevation of double the height will be produced: if two depressions meet, a depression of double depth will be produced; but if an elevation and a depression meet, the surface of the fluid will remain undisturbed, each counteracting the other. This mutual annihilation is denominated the *interference* of waves.

We have an illustration of the same thing on a large scale in the tides, the spring tide being the *sum* of the solar and lunar waves when they conspire; the neap tides their difference when they are opposed to each other. When stones are thrown into a pond, and two groups of waves cross each other on its surface, there are points at which the water remains immoveable when the two systems are nearly of the same magnitude, while there are other places in which the force of the water is augmented by their concurrence. If two sonorous undulations differ a little from each other in frequency, they alternately tend to destroy each other, and to acquire a double, or, perhaps, a quadruple force; and the sound gradually increases and diminishes in continued succession at equal intervals. This alternate intension and remission is called *a beat.*

In the same way, the waves of the luminiferous ether interfere, and, mutually destroying each other, cause darkness. This important fact, that under some circumstances, light added to light causes darkness — a fact apparently fatal to the projectile theory of light— was first established by Dr. Young. This distinguished philosopher, whose attainments and knowledge were insufficiently estimated while he was living, passed a sunbeam through a hole (O) made with a fine needle in thick paper, and brought into the diverging beam a slip of card (A B) one-thirtieth of an inch in breadth, and observed its shadow (E F) on a white screen, at different distances. The shadow was divided by parallel bands, but the *central*

Fig. 32.



line (X) *was always white.* That these bands originated in the interference of the light passing on both sides of the card, Dr. Young demonstrated by simply intercepting the light on one side by a screen (C D), leaving the rays on the other side to pass freely. In this arrangement all the fringes which had before existed in the shadow immediately disappeared, although the light inflected on the edge (A) was allowed to retain its course. The same result took place when the intercepting body was at *c d*, before the edge B of the body. These are the same as the internal bands represented in *fig.* 18.

By a series of wooden sliders, originally contrived by Young*, but put into a very convenient form for use in the lecture-room, by my friend Mr. Woodward, the interference of waves may be neatly illustrated. By this apparatus it will be seen that when the difference amounts to 2, 4, 6, or other even number of half-undulations, the waves coincide and mutually augment their intensities; while, when the difference amounts to 1, 3, 5, or other odd number of half-undulations, there is discordance and mutual destruction. Now, it will be perceived that these numbers coincide with those referred to by Newton, as expressive of his fits of transmission and reflection.

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* *Lectures on Natural Philosophy*, vol. i. p. 390., plate xxv., *fig*. 352., D.

If two waves of *homogeneous* or *monochromatic light* interfere, the result will be *an augmentation* or *diminution* of *brilliancy*, or *complete destruction.* The light is *augmented* when the waves accord, but is *lessened* or *destroyed* when they are mutually opposed. Hence Newton's rings, seen by homogeneous light, are merely dark and light bands of one and the same colour.

But if two waves of *heterogeneous* or *white light* interfere, the result will be *the production of vivid coloured fringes.* Certain colours are destroyed, while others remain or have their brilliancy augmented.

To this class of phenomena belong all those varied instances of *diffraction* to which we have before alluded. The general principle of interference may be stated under the two following heads:—

1. If two waves *coincide* or *conspire* in their movements at all their parts, the velocities of the vibrations, and consequently their intensities, will be doubled.

2. If the waves of one series be half an undulation either *in advance* or *behind* another series of waves, the velocities of the vibrations, and consequently their existence, are destroyed.

3. If waves of unequal length interfere, they cannot destroy each other. Their relative position throughout the group is not the same; and, though some vibrations are destroyed, others are augmented, and some are intermediately affected. Hence would be produced an effect analogous to the *beat* in music: but these alternations of weaker and stronger succeed each other with prodigious rapidity and produce in the eye a continuous sensation only. (See Fresnel, p. 125.)

[On the wave hypothesis we can easily explain the phenomena of diffraction before described. In the annexed diagram let light originate from a luminous point O, and diverge in circular waves from O as a centre, portions of which are represented by the concentric circular arcs; the dark lines corresponding to the crests of the waves, the dotted lines to the depressions. (See *fig.* 33.)

Now let such a series of waves encounter an obstacle A. At its edge a new set of waves will commence diverging in like manner in a circular form and similarly represented in the diagram. But the original waves also continuing to be propagated, these last will cross and interfere with them; and upon inspecting the figure it will be seen, that at all the points where a dark line crosses a dotted one there

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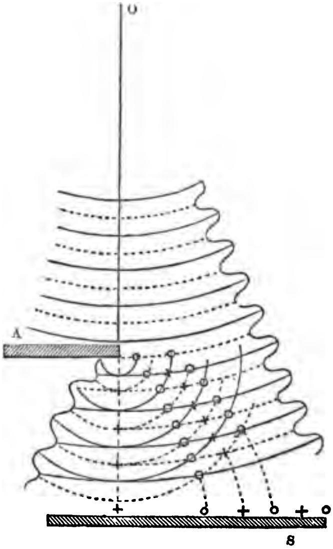
will be a *discordance* or mutual destruction of the waves, viz. at the points marked O;

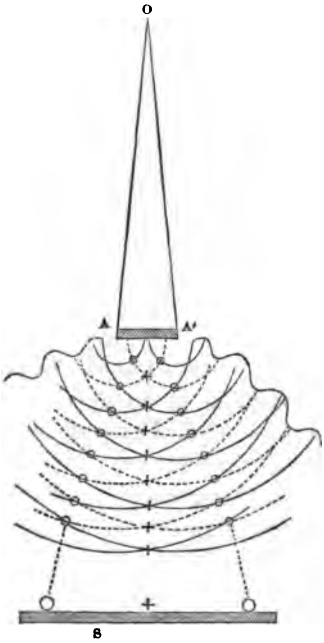
Fig. 33.



and wherever a dark line crosses a dark line, or a dotted a dotted line, there will be a point of accordance or double intensity marked +. Thus, if the light be received on a screen S at any distance, the image will consist of a series of bright and dark points at alternate distances from the edge.

What is here shown of one edge is easily extended to the case of two forming an aperture, or two opposite edges of the same opaque body, *within* whose shadow, in like manner,

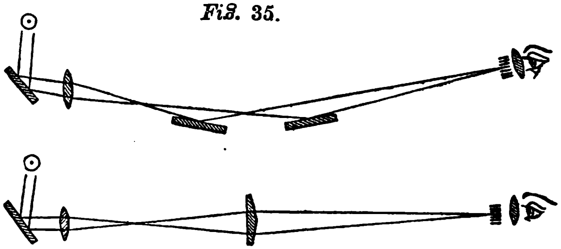
Fig. 34.



dark and bright stripes will be produced as in Dr. Young's experiment (*fig.* 33.).

It was also on the very same principle M. Arago established the abstract property, that any two rays originating from the same point will interfere, if made to cross at a very small angle, *without reference to the edge of any opaque body*, either by reflexion from two plane mirrors *very slightly inclined* to each other, or by passing through a *very flat* prism, when, in either case, a set of fine and well-defined dark and bright stripes are produced, and may be seen magnified by an eye-lens. The sun's light must be used, brought to a focus by a lens fixed in the shutter. The reflectors may be halves of the same piece of glass laid on a table, and one slightly pressed at its edge.]

Fig. 35.

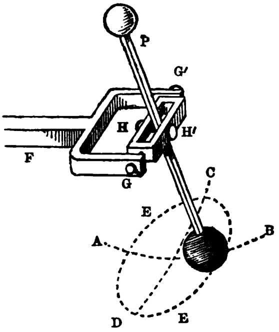


We come now to another very important case of interference. It is a law in dynamics, that a body acted upon by two forces united will describe the diagonal of a parallelogram in the same time in which it would have described its sides by the separate action of those forces. Hence, if two waves whose molecules are in the same phases of vibration, but whose planes of vibration are more or less angular, say rectangular, to each other, the only effect produced is an alteration of the plane of vibration.

Fresnel established the law, that "two rays of light, polarized at right angles to each other, exhibit none of the phenomena of interference;" that is, they produce no colours of fringes. But under certain conditions they will produce other effects, and these of a very remarkable kind. In a word, the superposition of two rectilinear vibrations at *right angles* to each other, *if they differ by* $\frac{1}{4}$ of a vibration in their phase, will produce, not a *rectilinear*, but a *circular* vibration.

It is often a difficult thing for the student to conceive how it is possible, by a combination of two *rectilinear* motions, to produce *curvilinear:* the following mechanical illustration, therefore, may not be useless, devised by the Editor, and of which no account has hitherto been published. (See *fig.* 36.)

Fig. 36.



An arm, F attached to any convenient support, terminates in two branches, on which, by the pivots G, G′, a small frame swings: in this frame, by the pivots H, H′, whose axis is at right angles to G, G′, a pendulum P can vibrate, having a weight at its lower end; and its upper, carried up to any convenient height, is terminated by a white ball, in order to render its motion conspicuous in the lecture-room.

Now, it is evident that, by means of the pivots H H′, the pendulum can *only* vibrate in the plane of C D. Again, by the pivots G G′ it can only vibrate in the plane of A B at right angles to the former. If now motion be communicated to it in one of these planes, and at an *instant after* in the other, the result of the compound motion in this discordance will be that it vibrates in *the ellipse* E E′, which will be a circle if the interval be exactly $\frac{1}{4}$ of a vibration.]

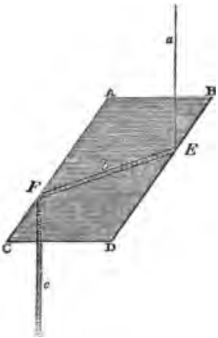
Thus, if we have a series of such vibrations forming two plane waves of equal intensity, polarized at right angles, and differing in their progress $\frac{1}{4}$ of an undulation, the result *in theory* is a circular wave. Now, in order that you may comprehend how we practically effect the circular polarization of light, I must beg of you to keep in mind these statements. Remember, that to convert plane-polarized into circularly polarized light, two conditions are necessary, namely, 1st, the existence of two systems of luminous waves of equal intensity, polarized perpendicularly to each other; and, 2dly, a difference in the paths of these two systems of an uneven number of quarter-undulations. Now, whenever these two conditions are satisfied, circularly polarized light results. But how are we to satisfy them? By so doubly refracting plane polarized light that the two resulting waves shall differ in their path an odd quarter-undulation.

There are five modes of effecting the circular polarization of light, that is, of satisfying the conditions above mentioned; but they all agree in acting on the principle now laid down, namely, that by them plane-polarized light is doubly refracted, and two rectangularly polarized waves produced, which differ in their path an odd quarter-undulation.

1. *Fresnel's Method.*—Fresnel effected the circular polarization of light by means of a parallelopiped of St. Gobin (crown) glass (*fig.* 37), whose acute angles B and C are about 54° and consequently whose obtuse ones A and D are about 126°. This apparatus is commonly called *Fresnel's rhomb.* If a ray *a* of plane polarized light be incident perpendicularly on the face A B, it will suffer two total internal re-

flections at an angle of about 54°, one at *E*, the other at *F*, and will emerge perpendicularly from the face D C. If the first plane, B D, of internal reflection be inclined 45° to the plane of polarization of the incident ray, *a*, the emergent ray, *c*, will be circularly polarized, or at any other inclination, elliptically.

Fig. 37.



Fresnel's Rhomb.

A B C D. Fresnel's rhomb.
a. Incident ray of plane polarized light.
b. Depolarized ray.
c. Circularly polarized ray.

It is hence also apparent that, by reversing the experiment, or causing circularly polarized light to enter the rhomb, it will emerge rectilinearly polarized, with its plane of polarization making an angle of + 45° or — 45° with the plane of reflection, according as the incident light was right or left-handed.

Let us now endeavour to explain this phenomenon according to the wave hypothesis.

So long as reflection is *partial*, whether performed at the first or second surface of the diaphanous medium, the incident light suffers only a deviation from its plane of polarization, without having its primitive properties altered, whatever may be the azimuth of its plane relatively to that of the plane of reflection.

But when the reflection is *total* the case is very different. The reflected rays then have, in general, suffered partial depolarization, especially if the plane of reflection is in an azimuth of 45° relatively to the primitive plane of polarization. Now, a ray of light thus modified, or depolarized as it is termed, may be represented by two rays polarized, the one according to the plane of reflection, the other perpendicularly to it. In other words, the incident-polarized ray (*fig.* 37., *a*) is resolved by reflection into two rectangularly plane-polarized rays (*b*), the planes of which are inclined respectively, the one 45° to the left, the other 45° to the right, of the plane of polarization of the incident ray.

But it is obvious that the reflection of these two rectangularly polarized rays must be effected at different depths, and, therefore, under very different circumstances. The ray whose vibrations are performed parallel to the reflecting surface will glide, as it were, on the surface, and be reflected in a stratum of uniform density; whereas the ray whose vibrations are performed perpendicularly to the reflecting surface, will penetrate to a greater depth, and pass into strata of varying density. The latter ray will, therefore, suffer a greater retardation than the

not in this condition till reflection has occurred, by his own hypothesis.

one whose vibrations are performed parallel to the reflecting surface.*

Now when, in the case of Fresnel's rhomb, the plane of the first reflecting surface is in an azimuth of 45° to that of the incident ray, the retardation is equal to $\frac{1}{8}$th undulation. The same ray is farther retarded another $\frac{1}{8}$th undulation by the second reflection; and now differs in its phase from that of the other ray $\frac{1}{4}$th of an undulation.

Thus are obtained the conditions necessary for the formation of a ray of circularly polarized light; namely, two plane rays of equal intensity, polarized in planes perpendicular to each other, and differing in their path $\frac{1}{4}$th of an undulation.

2. *Airy's Method.* — If a ray of plane polarized light be transmitted through a lamina of either mica or selenite of such a thickness that, for a ray perpendicular to the lamina (that is, the ray polarized in the plane of one of the principal sections of the mica), the ordinary ray shall be retarded an odd or uneven number of quarter-undulations, as $\frac{1}{4}$th, $\frac{3}{4}$ths, or $\frac{5}{4}$ths (according to the convenience of splitting), more than the extraordinary ray (that is, the ray polarized in the plane of the other principal section), the emergent light will be found to be

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* This explanation must be regarded as somewhat hypothetical.—Ed.

circularly polarized. In this case the incident light is resolved into two sets of vibrations at right angles to each other, and one of these is retarded in its phases more than the other.

Between this and Fresnel's method of effecting circular polarization there is this difference: in Fresnel's rhomb the retardation of the one ray is nearly the same for all colours, that is, for waves of different lengths. But in the case of the lamina of mica or selenite the retardation is greater for blue rays than for red rays. "This is seen most distinctly on putting several such laminæ together [in the same crystalline position], when the light which is reflected from the analyzing plate is coloured; whereas, on putting together several of Fresnel's rhombs, there is no such colour. It is plain that, in substituting such a lamina for Fresnel's rhomb, the plane of polarization of that ray which is least retarded corresponds to the plane of reflection in the rhomb."

3. *Dove's Method.* — This consists in transmitting plane polarized light through glass to which a certain degree of doubly refracting power has been communicated by pressure, or by rapidly heating or cooling it.

It has been shown that well annealed glass acquires doubly refracting properties when compressed; that unannealed glass possesses similar properties; and also that during the time that glass is rapidly heating or cooling it is likewise a double refractor.

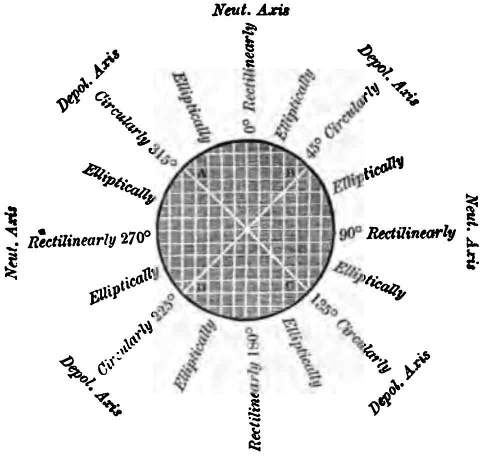
Of the two systems of waves which are thus obtained, one is polarized in a plane parallel to the axis of compression, the other in a plane perpendicular to it.

Now, if the degree of doubly refracting power thus communicated to glass be just sufficient to effect the retardation of one of the systems of waves $\frac{1}{4}$ of an undulation, we obtain a structure fitted for converting plane-polarized into circularly polarized light.

"If a square or circular plate of glass," says Dove, "be compressed so that the axis of compression forms an angle of 45° or 135° with the plane of primitive polarization, the light passing through the centre of the glass at a certain degree of the pressure will be circularly polarized. During a complete revolution of the plate in its plane round the perpendicular incident ray as an axis of revolution, the light is polarized four times rectilinearly and four times circularly: rectilinearly when the compressing screw acts on the points 0°, 90°, 180°, 270°, that is to say, when the axis of compression is perpendicular to the plane of primitive polarization, or lies within it; and, on the contrary, it is polarized circularly when that point of action corresponds to the points of division, 45°, 135°, 225°, 315°, whilst 45°, and 225°, as also 135°, and 315°, exhibit a similar effect."

These statements may be rendered more intelligible by the following diagram:

Fig. 38.



If light, rectilinearly polarized in the plane O° 180°, or in that of 90° 270°, be incident on a circular disk of compressed glass (*fig.* 38. A B C D), the emergent light is rectilinearly polarized when the axis of compression is either O° 180°, or 90° 270°; but is circularly polarized when the axis of compression is either 45° 225°, or 135° 315°. At all intermediate azimuths it is elliptically polarized.

The degree of compression to which the glass is to be subjected to produce these effects, is such that, when the compressed glass is placed in the polariscope, with the tourmalines crossed, a black cross is seen with blond-white vacant spaces in the corners.

Unannealed glass possessing the same degree of doubly refracting power acts in a similar manner to compressed glass.

Annealed glass, while either rapidly heating or cooling, likewise gives rise to similar effects at the time when its doubly refracting power is just equal to that of the compressed glass above described.

Airy's Analysis for circularly polarized Light.—To distinguish right-handed from left-handed circularly polarized light, Mr. Airy contrived an analysis which suppresses the one and transmits the other. "It is well known," he observes, "that if circularly polarized light is incident on Fresnel's rhomb it emerges plane polarized, and the position of the plane of polarization at emergence makes an angle of + 45° or—45° with the plane of reflection, according as the incident light was right or left-handed. Let the light emerging from the rhomb be received on an unsilvered glass at the polarizing angle, whose plane of reflection makes an angle of + 45° with that of the rhomb. Now it is plain that, if the light incident on the rhomb was right-handed it becomes plane-polarized in the plane of reflection of the glass, and therefore is wholly reflected; if it was left-handed, it becomes plane-polarized in the plane perpendicular to the plane of reflection of the glass, and therefore is wholly suppressed."

It is then obvious that this combination of Fresnel's rhomb and an unsilvered glass at + 45° or — 45° would form an analyzer for circularly polarized light. But as the rhomb is inconvenient on account of its length, Mr. Airy has substituted "a plate of mica of such thickness that the ray polarized in the plane of one of its principal sections is retarded either $\frac{1}{4}$th, $\frac{3}{4}$ths, or $\frac{5}{4}$ths of a wave length (according to the convenience of splitting) more than that polarized in the plane of the other."

The mica being attached to the unsilvered glass, so that its principal section makes an angle of 45° with the plane of reflection, an analyzer is produced which answers the same purposes in general as that described above.

On the wave hypothesis, in circular polarization the molecules vibrate or revolve uniformly in circles, and the form of the wave is therefore that of a circular helix.

But, apart from all theoretical ideas, the name is an appropriate one; for, unlike the rays of plane-polarized light, those of circular polarized-light have *no distinction of sides*, or in other words no particular relations to certain regions of space, but present similar properties on all sides.

In this property also circularly polarized light agrees with common or unpolarized light, but differ from plane or rectilinearly polarized light.

Analyzed by a doubly refracting prism of Iceland spar, a ray of circularly polarized light gives constantly *two equal images*, in whatever plane the principal section of the prism be placed. For, as already stated, a ray of circularly polarized light is the resultant of two rays whose vibrations are at right angles and differ by a quarter of an undulation: and, therefore it must give equal images of the doubly refracting prism, in the same way that common or unpolarized light does; for the difference of phases has nothing to do with this character. In this respect circularly polarized light agrees with common or unpolarized light, but is distinguished from plane-polarized light, which in certain positions (before specified) yields one image only.

1. A ray of circularly polarized light is

capable of reflection from a plane glass in every azimuth of the plane of reflection; for the circular vibrations of the ethereal molecules may be resolved into two equal rectilinear vibrations, one parallel, the other perpendicular, to any arbitrary plane. By this property, then, circularly polarized light differs from plane, but agrees with unpolarized light.

2. A ray of circularly polarized light is capable of transmission through a plate of tourmaline in every azimuth; for in this case also the circular vibrations resolve into two as before. One of these vibrations is transmitted by the tourmaline, the other suppressed.

Elliptically polarized light is produced when two rectangular systems of waves of equal intensity differ by a fractional number of quarters of an undulation. The wave so formed is like an elliptical helix.

There are several modes of procuring elliptically polarized light. If in Fresnel's rhomb, the angle between the planes of incidence and polarization be any other than 45°, the emergent ray is elliptically polarized.

Airy's method of producing circularly polarized light will give elliptical, if the mica plate be placed in an azimuth between that which yields circular and that which gives plane-polarized light.

Compressed or unannealed glass also gives elliptical polarization by Dove's method.

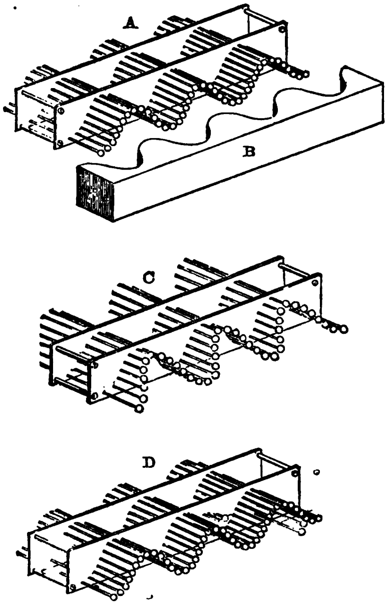
Plane-polarized light reflected from metals becomes elliptically polarized; that from silver is almost circular, that from galena almost plane.

If elliptically polarized light be analyzed by the Nicol prism, &c., it never vanishes, though at alternate positions it becomes fainter; and is thus distinguished both from plane and circularly polarized light. — If analyzed by calc-spar, in like manner neither of the images vanishes, but they undergo changes in intensity.

We have already shown that if two systems of waves of equal intensity, and polarized in rectangular planes, differ in their progress $\frac{1}{4}$ of an undulation, the compound movement which they will communicate to each molecule, instead of being *rectilinear*, as in the two fasciculi considered separately, will be *circular*, and will be performed with uniform velocity. But if the difference of progress, instead of being an even or an uneven number of $\frac{1}{4}$ths of undulations, be a fractional number, the vibratory movements will be neither rectilinear, nor circular, but *elliptical.*

Here is an apparatus (*fig.* 39), contrived by Professor Wheatstone, which illustrates how two rectangularly polarized rays of light may influence each other. It consists of a series of rods disposed horizontally in an undulated form, so as to represent a system of plane waves. One end of each rod is render conspicuous by a white ball; and it will be seen that, as now arranged, all the balls (which represent a line of etherial molecules) are in one

Fig. 39.



plane A. If now a block of wood B, cut so as to represent a system of plane waves of equal size to those represented by the rods, be pressed against the balls, so that the systems of waves act on each other in a rectangular direction, then, when the waves coincide, the plane in which the balls lie changes, and becomes diagonal, as in C; whereas, if the block be so applied to the balls, that the two systems of waves do not coincide, then the balls no longer remain in one plane, but become placed in a helicoidal manner, representing a circular or elliptical wave, as in D.*

With these remarks I finish the theory of light, and have now arrived at the subject of *Coloured Polarization.*

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* It should be noticed that the apparatus of Prof. Wheatstone has far more extensive applications than those here described: but these are perhaps sufficient for the purposes here in view. — Ed.

LECTURE II.

COLOURED POLARIZATION.

WHEN an excessively *thin film* of a doubly refracting crystal is placed in the polariscope, that is, between the *polarizing* and *analyzing* plates, the most gorgeous colour or colours appear, and when the analyzer is rotated on its axis they change to complementary tints. If the film be of uniform thickness, the colour is uniform; but if the film be of irregular thickness, different colours are peceived.

In order to produce colour, it is necessary to use, first, a *polarizer*, as a tourmaline, a doubly refracting prism, or a reflecting plate; secondly, a *film of a doubly refracting crystal*, called the *depolarizer;* and, thirdly, an *analyzer* or *test*, as a tourmaline, a reflecting plate, or a doubly refracting prism.

The office of the *polarizer* is indicated by its name; it polarizes the light. Without this no colour is perceived, for a reason which will be hereafter explained.

The *use of the analyzer* is to resolve the emergent light into two parts; of which one is *suppressed,* and the other, at least a definite portion of it, is wholly reflected to the eye.

By the common analyzing plate (an unsilvered glass reflector at the polarizing angle, or a plate of tourmaline, or a doubly refracting prism considered with reference to one pencil only) the emergent light is resolved (according to Fresnel's theory) into two sets of vibrations, one parallel to, and the other perpendicular to the plane of polarization of the analyzing plate: the former of these is wholly suppressed, and the latter is wholly transmitted to the eye.

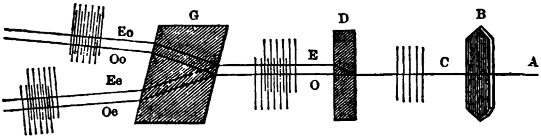
The *doubly refracting film,* called the *depolarizer,* receives the light thus polarized, and doubly refracts it. That is, a system of waves, constituting the incident ray, entering the crystalline film, is resolved into two systems of equal intensities within it. These form respectively the *ordinary* and *extraordinary* rays (*fig.* 40, O and E). They are polarized in planes + 45° and – 45° to that of the incident system, so that the plane of polarization of the ordinary system forms angle of 90° with that of the extraordinary system.

Now, the two systems of waves thus produced traverse the crystal in different directions and with different velocities; but, as the film or plate is excessive thin, they emerge superposed. One set proceeds through the crystal more slowly than the other; or, in the language of a distinguished writer on this subject, one set *lags behind the other;* so that at their emergence they are found to be in different phases of vibration.

By the *analyzer* each of the two systems (O and E) is resolved into two other systems (Oo Oe and Ee Eo), so that now four systems or two pairs are produced.

But the vibrations of these four systems are made in two planes: that is, two in one plane, and the other two in a second plane, which is rectangular to the first. Now, as the two vibrations which are made in the same plane are not in the same phase (the one system having suffered a greater retardation than the other), the waves interfere and produce colour (if the incident light be white). But the two vibrations of the one plane *conspire,* while those of the other plane are *opposed.* Hence the tint or colour produced by the interference of the waves in one plane, is complementary to that produced in the other plane. So that if the analyzer be a doubly refracting prism, both complementary colours are seen by transmission; but if it be a reflector, one is reflected and the other transmitted; whereas, if it be a tourmaline, one is transmitted, while the other is suppressed, extinguished or stifled.

Fig. 40.



Production of Complementary Tints.

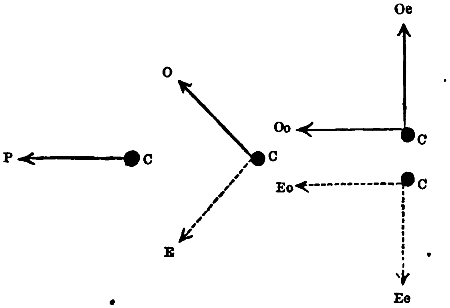
A. A ray of common or unpolarized light incident on B.
B. The polarizer (a plate of tourmaline).
C. A ray of plane-polarized light incident on D.
D. The doubly refracting film or depolarizer.
E. The extraordinary ray
O. The ordinary ray.
} produced by the double refraction of the ray C.
G. The analyzer (a doubly refracting prism).

Eo. The ordinary ray
Ee. The extraordinary ray
} produced by the double refraction of the extraordinary ray E.

Oo. The ordinary ray
Oe. The extraordinary ray
} produced by the double refraction of the ordinary ray O.

To render somewhat more intelligible the cause of the colours being complementary, and, therefore, to explain what is meant by the *conspiration* and *opposition* of vibrations, let us suppose the vibrations of the polarized light (C, *fig.* 40.) to be made in the plane C P, *fig.* 41.; and, to give more precision to our ideas, let us further suppose that the molecule C is, at a given instant, moving *from* C towards P.

Fig. 41.



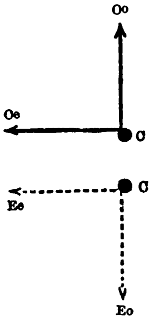
The doubly refracting film resolves this motion into two other motions, performed at right angles to each other, one in the direction C O, the other in the direction C E. The waves produced by the vibrations in the plane C O we shall suppose to constitute the *ordinary* system, while those in the plane C E form the *extraordinary* system. But the plate is much too thin to have produced between these two systems any sensible separation.

Each of these motions is resolved by the analyzer into two others at right angles to each other. That is, the vibration C O is resolved into the vibrations O Oo and C Oe; while the vibration C E is resolved into the vibrations C Eo and C Ee. Now, it is obvious, that the two motions C Oo and C Eo act in the same direction, or, in other words, they *conspire*, or *strengthen each other;* while the motions C Oe and C Ee, though performed in the same plane, *oppose* or *destroy* each other.

By rotating the analyzer the reverse happens: C Oo and C Eo *oppose* or *destroy* each other, while C Oe and C Ee *conspire*, or *strengthen each other*, as in *fig.* 42.

Thus, then, the original polarized ray (C, *fig.* 40.) has been resolved into four rays, two polarized in one plane, and the other two polarized in a plane rectangular to this. The two rays which interfere and destroy each other differ by half an undulation. The colour produced by the interference of the *conspiring* rays corresponds to the difference of the routes of the two polarized rays in the plate or film; while that which results from the interference of the *opposing* rays is that which is due to the same difference augmented or diminished by half an undulation. In the case above noticed, in which C Oe and C Ee (*fig.* 43.) are opposed, the

Fig. 42.



[illegible] when light is changed [illegible]
[illegible]

colour corresponds to the difference *plus* half an undulation. *

But it may be asked, What is the use of the polarizing plate? What is the reason that no colour is perceived if the light which is incident on the double refracting film be common or unpolarized? To explain this, let us suppose that a ray of common or unpolarized light consists of two rays rectangularly polarized. Each of these rays will suffer the same series of divisions, subdivisions, and interferences as the former; but the tints produced by the one ray will be complementary to those of the other; so that we shall thus obtain two pairs of complementary tints; and as the tints of each pair will emerge superposed, they will neutralize each other, and the resulting light will be of uniform whiteness.

Thus,

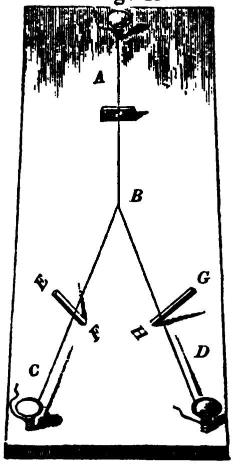
	1st PAIR OF TINTS.		2d PAIR OF TINTS.
Suppose the two complementary tints produced by one ray to be - -	Green	and	Red.
Those produced by the second ray will be - - - - -	Red	"	Green.
And the sum of each pair will be -	White.		White.

For red and green are complementary tints, and produce by their union white light, as I have already demonstrated.

The office of the doubly refracting film, called the depolarizer, is to doubly refract the polarized light. It prepares the rays for the changes which they have ultimately to undergo and by which colour is to be produced. The thickness of the film or crystalline plate determines the tint; but the actual thickness required to produce a given tint depends on the nature of the crystal. By this plate or film two rectangularly polarized systems of waves are produced, which traverse the plate in different directions and with different velocities, and emerge in different phases of vibration. Now, as they are superposed, and as the retardation amounts only to a few undulations and parts of an undulation, it might be supposed that colour would be produced by their interference. But I have already stated that two rectangularly polarized rays do not interfere, so as to produce colour. In order, therefore, to make them interfere, their planes of polarization must be made to coincide; and to do this is the function of the analyzer.

In order to assist us in comprehending how a polarized ray may be resolved into two others polarized in different planes, we may take, as an illustration, a stretched cord, *fig.* 43. *A B*, dividing at *B* into *B C* and *B D*, making a small angle with each other at *B*, and having equal or unequal tension. Let us suppose the extremity *A*, of the single cord to be made to vibrate regularly in either a horizontal or vertical plane; now, by means of two polished guiding planes, *E F* and *G H*, inclined at different angles to the horizon, and making a right angle with each other, the horizontal vibrations of the cord *A B*, will give rise to two other vibrations, parallel respectively to *E F* and *G H*. And if we assume the two branches *B C* and *B D* to be unequally tense, the waves produced by the vibration of *A B* will be propagated along them with unequal velocity. So that this illustration, which I have adopted from Sir John Herschel's able treatise on light, serves to explain not only how a vibration in one plane may be resolved into vibrations in two other planes, but also why the two resulting waves are propagated with unequal velocity.

Fig. 43.



Though a thin plate of *Iceland spar*, or of any other doubly refracting crystal serves, when placed in the polariscope, for the production of colour; yet certain crystals are preferable to others, on account of the facility with which they may be split into thin laminæ. *Selenite* and *mica* are especially convenient for this purpose; and the former of these is extensively employed by opticians in the preparation of a variety of beautiful and ingenious polariscope illustrations. On this account a brief notice of it is requisite.

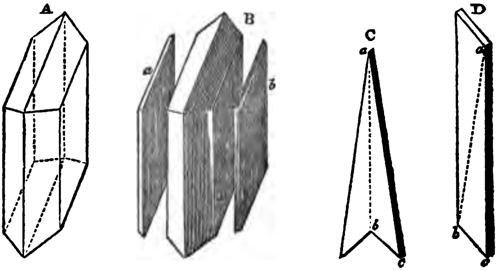
Selenite, or *sparry gypsum,* is the *native crystallised hydrated sulphate of lime* ($Ca\ O.\ S\ O_3 + 2\ Aq.$). It occurs imbedded in London clay. It is found also at Shotover Hill, near Oxford, where the labourers call it *quarry glass,* and likewise at the Isle of Sheppey. Very large crystals of it are found at Montmartre, near Paris. The crystalline forms in which it occurs belong to the oblique rectangular prismatic system. Haüy and the late Mr. William Phillips describe its primary form as a right oblique-angled prism; so that the lateral faces of the crystal are regarded by them as the terminal planes. But the optical characters of the crystal prove the incorrectness of the description of these celebrated mineralogists: and here, I would observe, is an excellent illustration of the great value of polarized light to the crystallographer. In this particular instance it enables him to distinguish a lateral face from a terminal plane of a prism.

The crystals of selenite which are most frequently met with are oblique rectangular prisms, with ten rhomboidal faces, of which two are considerably larger than the others (*fig*. 44. A). They are very easily slit into thin laminæ (*a b*, *fig*. 44. B), parallel to these larger lateral faces (terminal planes of Haüy and W. Phillips).

Macles, or *hemitrope crystals of selenite*, are very common. By hemitrope, a word derived from the Greek (from ἡμι *half*, and τρέπω *I turn*), is meant a figure produced by cutting the primary crystal in two, causing one of the fragments to make half a revolution, and then uniting the sides actually in contact. The most singular and common hemitrope variety of selenite is that called *arrow-headed selenite* (*fig*. 44. C), and which is so called because the crystal is formed like the barbed head of an arrow. Its nature may be easily explained. Cut a card or thin board in a rhomboidal form to represent one of the laminæ taken from lateral faces of the prism (*fig*. 44. D). Then divide it in the direction of its greater diagonal (*a b*), and transpose the separated parts in such a manner, that two of the alternate angles, produced by the diagonal division, shall make the point, the other two the barbs, of the arrow-head.

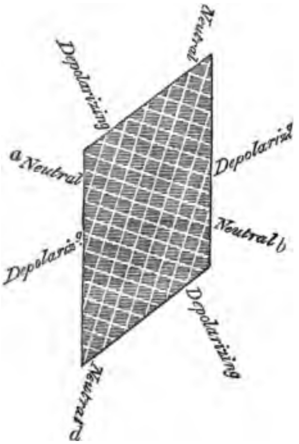
The optical structure of films or thin plates of selenite, having a thickness of from $\frac{1}{20}$th to the $\frac{1}{60}$th of an inch, is very curious. In two rectangular directions they allow perpendicular rays of polarized light to traverse them unchanged: these directions are called the *neutral axes*. In two other directions, however, which form respectively angles of 45° with the neutral axes, these films have the property of double refraction. These directions are usually denominated *depolarizing axes;* but they might be more correctly termed *doubly refracting axes.*

Fig. 44. *Selenite.*



In order to render these properties more intelligible, suppose the structure of the film to be that represented by *fig.* 45., in which the film is seen to be crossed by two series of light lines, or passages, the one perpendicular to the other. These are to represent the *neutral axes.* We may imagine, that in these directions only can the ethereal molecules vibrate. A ray of incident polarized light whose vibrations coincide with either of these lines is transmitted through the film unchanged. But a ray of incident polarized light whose vibrations form an angle of 45° with these lines, or, in other words, which coincide with the diagonals of the square spaces, suffers double refraction; that is, it is resolved into two vibrations, one parallel with *a b*, the other parallel with *c d*, and, therefore, the directions of the diagonals of the squares are called the *doubly refracting* or *depolarizing axes*. But the two

Fig. 45. *Imaginary Structure of a Plate of Selenite.*



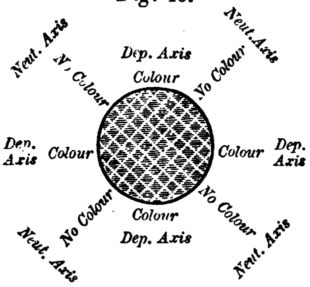
resulting vibrations are not propagated, in these two rectangular directions, with equal velocity, the one suffering greater retardation than the other; so that the waves, at their emergence, are in different phases of vibration, though they do not interfere so as to produce colour, because their planes of vibration are rectangular. By the analyzer, however, their planes are made to coincide, and colour is produced; and, on rotating the analyzer on its axis, the colour changes and becomes complementary.

To illustrate these statements, place a film of selenite, of uniform thickness, in the polariscope. On rotating the film (the analyzer and and polarizer remaining still), a brilliant colour is perceived at every quadrant of a circle, but in intermediate positions it vanishes altogether. We observe, however, that the tint does not change, but only varies in intensity. If, now, the film be fixed and the analyzer rotated, we also observe colour at every quadrant of a revolution; but the tint changes and becomes complementary at every quadrant—the same tint reappearing at every half-revolution: so that when the film alone is revolved one colour only is seen, but when the analyzer alone is revolved, two colours are seen.

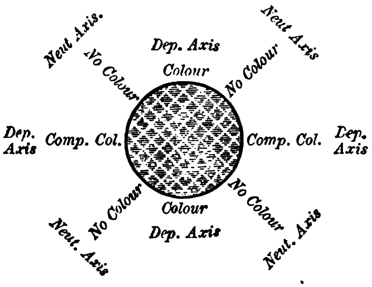
If we employ, as the analyzer, a double refracting prism, we observe two complementary disks of colour, and these may be made to cross and produce white light, as before shown.

Effect of revolving the Film of Selenite.

Fig. 46.

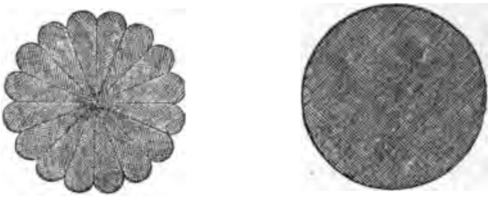


Effect of revolving the Analyzer.



The thickness of the film of selenite determines the particular tint. If, therefore, we use a film of irregular thickness, different colours are presented by different thicknesses. A wedge-shaped piece will produce parallel bands of colours, and two wedges crossed present diagonal bands. A plano-concave film, as well as a plano-convex film, gives concentric rings of colour, the former with a black, the latter with a white, centre.

Fig. 47.

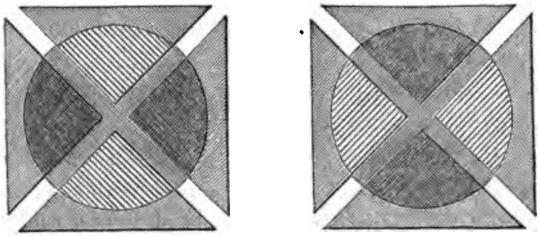


Star formed of 16 *pieces of Selenite.*

Plate of Selenite of uniform thickness.

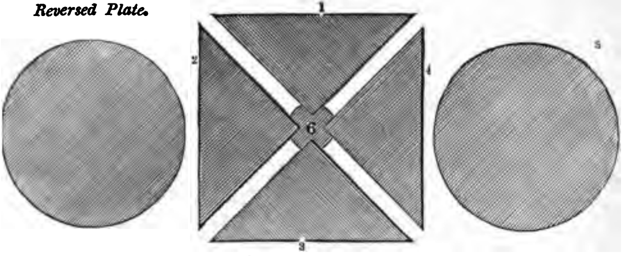
Two films superposed do not give the colour which would arise from the mixture of the two colours, but either the colour which corresponds to the joint thickness of the films, or that which belongs to the difference of their thickness. When the two films are put together, as they lie in the crystal, the resulting colour depends on the *sum* of the thicknesses. But when the two films are crossed, so that similar lines in the one are at right angles to similar lines in the other, the resulting tint depends on the *difference* of the thicknesses. These facts admit of very beautiful, curious, and interesting illustrations. Thin films of selenite of uniform thickness are so arranged as to slide over figures also formed of films of selenite. The changes of colour effected in the tints are most striking, and to unphilosophical minds almost magical.

Fig. 48.



In the opticians' shops are met with a great variety of devices prepared with films of selenite of different thicknesses, and which constitute philosophical toys illustrative of the before-mentioned facts. *Gothic windows, stars, flowers, fruits, animals* (butterflies, parrots, dolphins and chameleons), and *theatrical figures*

Fig. 49.



(Jim Crow, harlequin, &c.), are some of the ingenious, and often laughable illustrations contrived by Mr. Darker.

For illustration take the *Maltese cross* (see *fig.* 49.). All four arms are of the same thickness of selenite; but two only are placed in the same crystallographical position, the other two being in a perpendicular position. The tints of all four arms are alike; the centre piece 6 is a different thickness.

If, now, the selenite plate (5) be superposed on the cross, the results will be as follows:— The colours of 2 and 4 will be the *sum* of the thickness of 2 + 5 and 4 + 5, because the crystallographical position of 2, 4, and 5 coincide.

But the colours of 1 and 3 will be the *difference* of the thickness of 1 − 5 and 3 − 5; because the crystallographical position of 5 is at right angles to both 1 and 3.

If now the film 5 be reversed, the effects are all reversed.

Test of Double Refraction. — From the preceding statements, then, it appears that the polariscope becomes a very delicate test of double refraction. A very large number of crystalline, and other bodies, possess a doubly refractive property; but comparatively few of these have it in so high a degree as to present, under ordinary circumstances, the phenomenon of double images; that is, the separation of the two systems of ethereal waves is not, in general, sufficiently great to be visible to the eye. In such cases, therefore, the polariscope is of great value, since it enables us to detect the slightest degree of double refraction. Some doubly refracting bodies present, in the polariscope, most gorgeous colours, as selenite. Others, however, which possess the doubly refractive property in a much lighter degree, require the aid of a thin film of selenite of uniform thickness. Their double refractive property then becomes evident by the change which they induce in the colour of the film. Without this, we see light or dark fringes or bands, or black or white crosses, but not colour.

A correspondent of the author has communicated some curious observations on polarized tints developed under the following circumstances:—He states that a great variety of bodies produce colour when placed over selenite in the polarizing microscope, provided a *biaxial prism* of moderate separating power be used instead of the Nicol prism or tourmaline in an analyzer.

" Thus air bubbles in the balsam, scales of insects, sections of wood, pieces of seaweed, &c., which produce no colours under ordinary circumstances are by this plan coloured in the most gorgeous style possible; of course, if the object be small, two separate images are seen, one red, the other green (or other tints dependent on the selenite). Animalculæ floating in water are very interesting objects."

The field is white in the centre with a lunated edge of red on the one side and green on the other.

The peculiarity is, Why are not colours produced by the same object, when the tourmaline or Nicol prism analyzer is used? This distinction does not seem to be explained.

Cause of Double Refraction.—Being now in possession of an exceedingly delicate test of double refraction, we are prepared to enter into an inquiry into the cause of this property.

Now, we shall find that every body endowed with equal elasticity in every direction, is a single refractor. Alter its elasticity in any one direction, put it in a state of unequal tension, and immediately it acquires the property of double refraction. Hence, then, double refraction may be temporarily or permanently communicated to bodies, by temporarily or permanently disturbing the equality of their elasticity in different directions.

1. *Pressure produces Double Refraction.*—In fluids (gases and liquids) pressure is equally

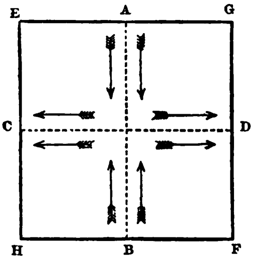
distributed in all directions, which is obviously owing to the facility with which the molecules shift their places. Hence pressure on fluids does not communicate to them the power of double refraction.

In solids, however, matters are far otherwise. Owing to cohesion, the molecules cannot change their relative positions; and, therefore, in this form of matter unequal degrees of tension may exist in different directions: so that pressure may be communicated in any desired direction without being equally or uniformly distributed.

Now, a transparent solid, as a well-annealed piece of glass, all of whose parts possess equal elasticity, is a single refractor; but if we subject such a body to the influence of a compressing force, it becomes a double refractor, and acquires neutral and doubly refracting (depolarizing) axes; the former parallel and perpendicular to the direction of pressure, the latter 45° inclined to them.

Let us consider for a moment what must be the effect of pressure in any given direction. Suppose a rectangular piece of glass (*fig.* 50.) to be subjected to pressure in the direction A B, the immediate effect will be to urge the contiguous particles nearer together in this direction, and thereby to call into action their repulsive forces. But it will also urge the particles asunder in the direction C D, that is, in a direction perpendicular to that of the pressure, and thereby to call into operation their attractive forces. Thus, then, it is obvious, that a force which, when applied to a solid, causes a condensation in the direction of the force (A B), is attended with dilatation or expansion in a direction perpendicular to it (C D). In the first direction the elasticity is a maximum, in the second direction it is a minimum. Incident light polarized in a plane parallel with either of these directions passes through unchanged, and these directions are called the *neutral axes.* But if it be polarized in a plane inclined 45° to either of these directions (that is, in the direction E F or G H), it is resolved into two systems of waves, one polarized in the direction A B, the other in the direction C D. The directions E F and G H are, therefore, the *doubly refracting* or *depolarizing axes.* But the system polarized in the plane A B, will proceed more slowly (owing to the maximum elasticity in that direction) than the system C D (which is polarized

Fig. 50.



in the direction of the minimum elasticity). Hence, at their emergence, the two systems of waves are in different phases of vibration, but they do not interfere so as to produce colours, owing to the plane of vibration of the one being rectangular or perpendicular to that of the other. When, however, we apply the analyzer, and restore these two rectangular planes to a common plane, interference takes place and colour results.

Let us now take the case of a flexed body. When I bend a cane or other solid, the convex surface is in a state of expansion or dilatation, while the concave surface is compressed. The molecules on the convex surface are urged asunder, and their attractive forces called into operation, while those on the concave surface are pressed together, and their repulsive forces brought into action. Between these two oppositely affected surfaces there is a neutral line, where equilibrium exists, and on both sides of this the degree of strain augments as we recede from the line. Now, if a well annealed, and, therefore, single refracting, plate of glass be bent, and examined while in the polariscope, it will be found to have acquired, while in the bent state, double refracting properties. Two sets of coloured fringes are perceived, one on the convex or dilated side of the plate, and the other on the concave or compressed side. Between these two sets of fringes is a black line, indicating the situation where neither compression nor dilatation exists, and where, therefore, double refraction is absent.

Thus, then, the polariscope becomes a valuable means of detecting the existence of unequal tension or strains in transparent bodies, and Sir D. Brewster has suggested its useful application to the determination of the intensity and direction of all the forces which are excited by a superincumbent load in different parts of the arch, as also the intensity and direction of the compressing and dilating forces which are excited in loaded framings of carpentry. For these purposes, models in glass or copal are to be prepared, and the effects are rendered visible by exposing the models to polarized light. He has likewise constructed a *chromatic dynamometer* for measuring the intensities of forces, founded on the facts already stated. It consists of a bundle of narrow and thick plates of glass, fixed at each end in brass caps. Then when any force is applied to a ring in the middle of the plates, the ends being fixed, the plates of glass will be bent, and the force thus produced is measured by the tints that appear on each side of the black line.

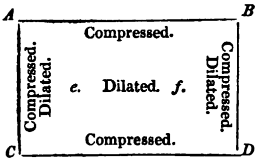
By the gradual induration, as well as by the mechanical compression and dilatation of animal jellies, fringes may be produced, as in glass.

2. *Unequal heating causes Double Refraction.* —When heat is applied to bodies it causes them to expand or dilate. If the substance to which the heat is applied be a bad conductor, the part in contact with the heated body becomes hot, and expands before heat is communicated to the neighbouring parts. Hence the bad conductor endeavours to curve, just as when we heat a compound bar of iron and brass a curvature is induced, owing to the unequal expansive power of these two metals; and as the brass expands more than the iron, the latter forms the inner or concave side of the curved bar, while the brass forms the outer or convex side. On this principle is constructed the compensation balance of a watch.

Glass is a bad conductor of caloric, and when a heated body is applied to it, the part in contact with this becoming hot, expands, but owing to the bad conducting quality of the medium, the surrounding parts not being influenced by the heat, do not expand, but resist the dilatation of the heated portion. In this way, therefore, the immediate effect of heat on one part of a piece of glass is to put all the surrounding parts into a strained state; one part is expand-ing, and other parts are resisting the dilatation. When the difference of temperature is extreme, the violence of the strain is such that very thick pieces of glass are sometimes rent asunder.

It is very desirable that we should be acquainted with the precise mechanical condition of the glass thus partially subjected to caloric. A knowledge of this would greatly assist us in comprehending the optical phenomena. But the subject is replete with difficulties. Perhaps some assistance may be obtained from the following considerations: —

Fig. 51.



Let *A B CD* (*fig.* 51.), be a rectangular plate of glass, subjected to heat along its edge *A B*. This portion of the glass being heated, tends to expand: but on account of its connection with other portions of the glass, cannot do so without forcing these to participate in its augmented bulk. These, however, owing to the bad conducting power of the glass, retain their original temperature, and consequently refuse to expand, so that the stratum is subjected to compression; that is, it is prevented from acquiring that volume which is natural to it in this heated state. The central stratum *e f* is in a state of dilatation or expansion, owing to its particles being urged asunder by the tendency of the upper stratum, *A B*, to expand. The resistance offered to the expansion by *e f* tends to produce pressure on the lower stratum *C D*, the particles of which will be urged together. This lower stratum *C D*, like the upper one *A B*, will then be in a state of compression. As the tension of *e f* is sustained at *A B* and *C D*, it will tend to send inwards the lateral columns *A C* and *B D*, dilating them at the convex portion of the bend, and compressing them at the concave portion. By these strains, therefore, the rectangular plate of glass will assume a figure concave on all its edges.

It is obvious then, from the unequal states of tension of the different parts of a piece of glass thus partially heated, that it ought to acquire doubly refracting properties, and the polariscope shows that it does so. In this state the glass exhibits distinct *neutral* and *doubly refracting* (*depolarizing*) *axes*, the neutral ones being parallel and perpendicular to the direction in which the heat is propagated. The black fringes, sometimes called lines of no polarization, indicate the neutral axes, or those portions of the glass which are destitute of the property of double refraction.

It deserves especial notice that fringes make their appearance in the part of the glass most distant from the heated body, before they have received any sensible accession of heat, and which, therefore, must depend on the state of strain into which they are thrown by the effect of the heat on the other parts of the mass, in the way I have already endeavoured to explain.

Sir D. Brewster has suggested the construction of two kinds of *chromatic thermometers*, for measuring changes of temperature by the production of coloured fringes, exhibited by glass plates when exposed to heat; for " every tint in the scale of colours has a corresponding numerical value, which becomes a correct measure of the temperature of the fluid." In the one instrument, the tints originate immediately from the changes of temperature; in the other, they are produced by the difference of pressures upon the glass, occasioned by the difference of expansions arising from changes of temperature. I must refer you to his paper in the *Philosophical Transactions* for 1816, for details respecting them.

3. *Unequal cooling causes Double Refraction.* — If a piece of hot glass of uniform temperature be unequally cooled, as by placing one of its edges on a cold mass of iron, it acquires doubly refracting properties, and when examined by polarized light presents fringes, &c., simi-

lar to those observed in glass unequally heated. It is obvious, however, that as the physical condition produced by cold is diametrically opposite to that caused by heat, so the structure of the corresponding parts of the two glasses (the one which has been cooled, and the other which has been heated) must be opposite.

4. *Unannealed Glass is a Double Refractor.* — If glass be suddenly cooled after having been melted, it possesses certain remarkable properties, which unfit it for ordinary use. Sometimes it splits or flies to pieces in the act of cooling; or if it fail to do this, a very moderate change of temperature, a slight external force, a scratch, or a slight fracture, is sufficient to cause it to crack and fly to pieces. The glass tears called *Rupert's drops*, or *hand-crackers*, and the *proofs*, or *philosophical phials*, are familiar illustrations of this kind of glass. In order to prevent it acquiring this remarkable condition, glass, after being fashioned, is submitted to the process called *annealing*, that is to very slow cooling in the annealing oven or lier. Glass which has undergone this process is said to be *annealed*, while that which has not is termed *unannealed*. But the so-called unannealed glasses sold by the opticians are in fact annealed glasses, which have been reheated until they begin to soften, then cooled by placing them on

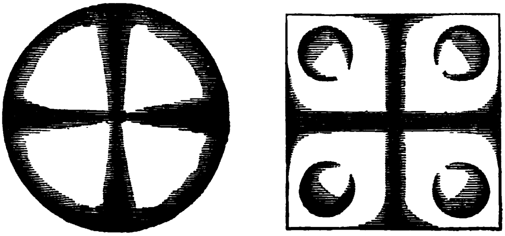
the ashes beneath the furnace, and afterwards ground and polished.

The optical properties of unannealed glass are very remarkable. To comprehend them let us consider the mechanical condition of the glass. When a mass of red-hot and soft glass is exposed to a cool air, its external portion becomes cold and rigid, while the inner parts are still hot and soft. After a short time, however, the latter solidify and cool, but are prevented from contracting themselves into the smaller bulk which is natural to them in their cooled state, by the rigid crust, which acts like an arch or vault, and keeps them distended, but which is to a certain extent strained and drawn somewhat inwards by the tension exercised on it by the internal parts. It is obvious, then, that the different parts of a mass of unannealed glass are unequally and differently strained; the internal being in a state of distention or dilatation, the external in that of compression. So that the state of the different parts, and the distribution of the forces, will be almost exactly similar to those already described, in the case of annealed glass which has been unequally heated. "The analogy between the cases," says Sir John Herschel, "would be complete, if, instead of supposing the annealed plate heated at one edge only, the heat were applied to all the four simultaneously, by surrounding it with a frame of hot-iron."

There is one very important point in reference to these unannealed glasses, to which I must beg your attention; I refer now to the circumstance that in them, *the polarizing* (doubly refracting) *structure depends entirely on the external form of the glass plate,* and on the mode of aggregation of its particles. This will be very obvious by observing the different shapes of the fringes respectively presented by square, circular, oval, rectangular, and other shaped plates. The circular and square plates have only one axis of [no] double refraction; whereas the oval and rectangular plates have two axes. By dividing and subdividing these plates the doubly refractive property is not only greatly diminished, but sometimes even destroyed, if the portion be very small. Moreover, it is distributed in a new manner, according to the shape of the fragment. The dissected unannealed glasses, sold in the opticians' shops, beautifully illustrate the dependence of the form of the coloured fringes on the external shape of the glass. Thus the pattern produced by one circular piece of unannealed glass, is very different to that of a circle formed by joining four segments. See *fig.* 52.

In these particulars the unannealed plates of glass differ very widely from doubly refracting crystals. The fringes and colours presented by the latter are unaltered by the changes we may effect in the external form of the crystal, the smallest fragment producing the same system of fringes as the largest; and, provided the thickness remains the same, the polarizing force suffers no diminution by the reduction in size.

Fig. 52.



We are then constrained to infer that the optical properties of crystals are those of their integrant molecules; while those of the unannealed glasses depend on the mode of arrangement of the molecules, and on the external form of the mass.

The effects produced by superposing similarly shaped pieces of unannealed glass are striking, and, at first, surprising; but, on consideration, may be easily understood. If they be symmetrically superposed, similar points being laid together, the tints will be equal to the sum of the separate tints: but, if superposed crosswise, the resulting tints will be the difference of the separate tints. This may be conveniently shown by causing an unannealed glass bar to rotate in front of another unannealed bar.

Applications.—These facts respecting the properties of unannealed or imperfectly annealed glasses, admit of some valuable practical applications. To the optician it is of the highest importance that the glass, of which lenses and prisms are made, should possess uniform density, and be free from all defects arising from irregularities in the annealing process. To detect these the glass should be carefully examined by polarized light previous to being ground and polished; and by this agent the slightest defects are made appreciable.

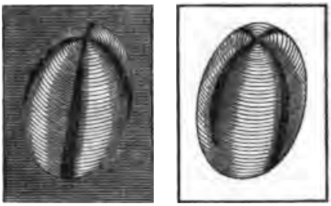
So also glass vessels employed for domestic purposes may be advantageously tested by the same agent. The facility with which tumblers, &c., crack, sometimes spontaneously, at other times while in the hands of the glass-cutter, or when warm water is poured into them, or when exposed to a slight blow, depends on some imperfection in the annealing process. Hence, also, the reason why *run glass* (that is, glass made without paying the duty) is very apt to crack; for, owing to the rapidity with which all the stages of its manufacture have been hurried on, it is not well made, and sufficient time has not been allowed for the annealing process.

It is probable, also, that manufacturers, or rather the mounters of electrical machines, might beneficially avail themselves of polarized light in the selection of glass cylinders and plates. Recently made cylinders, when mounted, will sometimes crack, or fly, as it is termed, without any obvious agency; owing, I presume, to some defect in the annealing process, which, perhaps, might have been previously discovered by means of polarized light.

An argument in favour of the vegetable origin of the diamond has been founded by Sir D. Brewster, on the phenomena presented by this substance, when examined by means of polarized light. It is well known that various opinions have been held by different writers on the mode of formation of this mineral. All of them, however, may be included under two divisions: those which assume the diamond to be the direct produce of heat on carbonic acid or carbon, and those which ascribe it to the slow decomposition of plants. Sir D. Brewster, who adopts the latter notion, met with a diamond which contained a globule of air, while the surrounding substance of the diamond had a polarizing (doubly refracting) structure, displayed by four sectors of polarized light encircling the globule. He, therefore, inferred that this air-bubble had been heated, and by expansion had produced pressure on the surrounding parts of the diamond, and thereby communicated to them a polarizing structure. Now, for this to have happened, the diamond must have been soft and susceptible of compression. But as various circumstances contribute to prove that this softness was the effect of neither solvents nor heat, he concluded that the diamond must have been formed, like amber, by the consolidation of vegetable matter, which gradually acquired a crystalline form by the influence of time and the slow action of corpuscular forces.

Starch grains have a laminated texture, and possess a doubly refractive power. They are composed of concentric layers of amylaceous matter. On some part of the surface of each grain is a circular spot, called the *hilum*. This appears to be an aperture or transverse section of the tube or passage leading into the interior of the grain, and by which the amylaceous matter, forming the internal laminæ, was conveyed. On examining the grains by the polarizing microscope, unequivocal evidence of their doubly refractive power may be obtained. At least I have found this to be the case in all the starches which I have yet examined, viz., *tous les mois*, potato-starch, West Indian arrow-root, sago-meal, Tahiti arrow-root (obtained from a species of *Tacca*), tapioca-meal, East 'Indian arrow-root (*Curcuma angustifolia*), wheat-starch, Portland arrow-root (*Arum maculatum*), and rice-starch. The larger grained starches form splendid objects for the polarizing microscope; *tous les mois* being the largest may be taken as the type of the others. It presents a black cross, the arms of which meet at the hilum. On rotating the analyzer the black cross disappears, and at 90° is replaced by a white cross; another, but much fainter black cross, being perceived between the arms of the white cross. Hitherto, however, no colour is perceptible. But if a thin plate of selenite be

A. *Fig.* 53. *B.*



Grains of Tous les Mois viewed by the Polarizing Microscope. *A* represents the appearance when the planes of polarization of the polarizer and analyzer are at right angles to each other; *B* when they coincide.

interposed between the starch grains and the polarizer, most splendid and gorgeous colours make their appearance. The arms of the cross acquire the colour which the selenite plate yields in polarized light. The four spaces between the arms also appear coloured; but their tint is different to that of the cross. The colours of the first and the third spaces are identical, but different to those of the second and fourth, both of which have the same tint. At the point where the colours of the arms and of the interspaces meet, the tints blend. All the colours change by revolving the analyzer; and become complementary at every 90°. If grains of Canna edulis be *heated* they lose their cross and polarizing structure.

The appearances presented by potato-starch are similar to those of *tous les mois.* Several other starches (as West Indian arrow-root, sago-meal, Tahiti arrow-root, tapioca-meal, and East Indian arrow-root) present black and white crosses, and, when a selenite plate is used, also colours; but in proportion as the grains are small, are their appearances less distinct. I have not hitherto detected the black and white crosses in wheat-starch, Portland arrow-root, and rice-starch. Their double refractive power, however, is proved by the change they effect in the colour yielded by a plate of selenite.

A great variety of animal structures possess a doubly refracting or depolarizing structure, as a quill cut and laid out flat on glass, the cornea of a sheep's eye, a piece of bladder, gold-beaters' skin, human hair, a slice of a toe or finger nail, sections of bones, of teeth, &c. The crystalline lenses of animals also possess this property in a high degree, owing to their central portion being denser and firmer than the external portion. If the lens of a cod-fish be placed in a glass trough of oil or Canada balsam, it presents twelve luminous sectors separated from each other by a black cross. Even living animals present double refracting properties. The aquatic larvæ of a gnat, commonly called *skeleton larvæ,* form a very amusing exhibition. They are to be placed in water in a very narrow water-trough. In certain positions they give no evidence of double refraction, but in others, and especially when they are exerting much muscular energy, they possess it in a very marked degree.

LECTURE III.

DOUBLE REFRACTIVE AND OTHER ALLIED PROPERTIES OF CRYSTALS.

In my last lecture I explained the nature and cause of double refraction; and I now proceed to examine the double refractive property of crystals, and to show how this is connected with, or related to, other properties of crystalline substances.

1. *Double Refraction of Crystals.*—Every transparent crystalline body refracts the rays of light which are incident on it at oblique angles; and the degree of its refractive power depends on two circumstances, viz., the angle of incidence, and the nature of the crystalline substance. In these respects crystals agree with all other transparent media.

But a very large number of crystals possess the property of double refraction; and they are, therefore, called *doubly refracting crystals,* to distinguish them from others which have not this property, and which are denominated *singly refracting crystals.*

The double refraction of some crystals is immediately manifested by the production of duplicate images; either through two parallel surfaces, as Iceland spar, or through two surfaces which are more or less inclined on each other. Thus, to observe the double refraction of a crystal of quartz, it is necessary to look through a pyramidal and lateral plane at the same time. By this contrivance the surface of emersion is inclined to that of admission, which causes the two pencils to emerge at different inclinations, and so become further separated as they proceed.

Many crystals, however, possess the property of double refraction in so feeble a degree that it is impossible to see, under ordinary circumstances, two images; and in such cases we are constrained to employ the polariscope to detect this property.

In every doubly refracting crystal there are one or more positions or directions in which the two images become superposed; or, in other words, in which no double refraction exists or is evident. These directions are called the *optic axes* or *the axes of double refraction.* I have already stated that the phrase *axes of* NO *double refraction* would be more intelligible. These axes may be regarded as positions of equilibrium where certain forces, which exist within the crystal and act in opposition, balance each other. In crystals of certain forms they coincide with the geometrical or crystallographical axes, whereas in crystals of other shapes they do not; but to these points I shall again have to beg your attention.

If we consider doubly refracting crystals in regard to the number of their optic axes we may divide them into two orders; one including those that possess only one axis, and another comprehending such as have two axes. The first are called *uniaxial*, the second *biaxial* crystals. As this distinction is connected with other remarkable optical peculiarities, as well as with the geometric and thermotic properties of crystals, it will be necessary to notice it a little more in detail.

a. Uniaxial Crystals.—Those crystals which have only one axis of [no] double refraction, and which, in consequence, are termed *uniaxial crystals*, or *crystals with one optic axis*, belong to the square prismatic or rhombohedric systems. In them the geometric or crystallographic axis is coincident with the optical one; that is, the line or direction in the crystal, around which the figure is symmetrically disposed, or about which everything occurs in a similar manner on all sides, is coincident with the optic axis, or the axis around which the optical phenomena are the same in all directions. You must not, however, suppose that the axis is a single line; for there must be as many axes as there may be lines parallel to each other, so that the word is merely synonymous with a fixed direction.

In all other directions but the one called the optic axis, these crystals doubly refract; and of the two rays thus produced, one follows the ordinary laws of simple refraction, and is accordingly called the *ordinary ray*, while the other, being subject to an extraordinary law, is denominated the *extraordinary ray.*

These two rays advance with unequal degrees of velocity; the one suffering greater retardation than the other. When the *ordinary* ray advances more rapidly than the extraordinary one, the crystal is said to have a *negative* or *repulsive axis of* [*no*] *double refraction;* but when the ordinary ray advances less rapidly, the crystal is said to possess a *positive* or *attractive axis.* In other words, when the extraordinary ray is refracted *towards* the axis, the crystal is said to have a *positive* axis; but when the ray is refracted *from* the axis, the crystal is said to have a *negative* axis. These terms are not very expressive of the property they are intended to represent. Biot used the terms *attractive* and *repulsive* to designate the attractive or repulsive forces which he supposed to emanate from the axes of crystals. For it is obvious that if the extraordinary ray be most retarded, it will be refracted from the axis, that is, it will appear to be repelled by a force emanating from the axis; whereas, if it be the least retarded, it will be refracted towards the axis, or will appear to be attracted by a force emanating from the axis. Now it was to obviate the hypothesis which these terms involve, that Brewster substituted the words *positive* and *negative* for the terms *attractive* and *repulsive*, merely meaning to denote by them the opposition, but not the nature, of the forces.

Table of Uniaxial Crystals.

Negative (—) *or repulsive Crystals.* (Extraordinary ray most retarded.)	*Positive* (+) *or attractive Crystals.* (Ordinary ray most retarded.)
Iceland Spar.	Zircon.
Tourmaline.	Quartz.
Nitrate of Soda.	Oxide of Tin.
Bicyanide of Mercury.	Ice.

In uniaxial crystals the position of the optic axis is constant, whatever be the colour of the light; whereas in biaxial crystals this is not the case, as I shall presently show.

b. Of Biaxial Crystals.—A very large number of crystals, including all which belong to the right-rhombic prismatic, oblique prismatic, and doubly oblique systems, have two axes of double refraction, which are more or less inclined to each other. Such crystals are, in consequence, denominated *biaxial crystals*, or *crystals with two optic axes*. In them there is no single line or axis around which the figure is symmetrical, as in uniaxial crystals; and the optic axes do not always, or even frequently, coincide with any fixed line in the crystals. Now this fact has led Sir D. Brewster to believe that the optic axes are not the real axes of the crystals, but only the resultants of the real or *polarising axes*, or lines, in which the opposite actions of the two real axes compensate each other. Hence he terms them the *resultant axes*, or *axes of no polarization*, or *of compensation*.

The following is a list of a few biaxial crystals; and for a more extensive one I must refer my auditors to Sir D. Brewster's works:

Table of Biaxial Crystals.

	*Character of Principal Axes.**	*Inclination of Resultant Axes.*
Glauberite	Negative	2° or 3°
Nitrate of Potash	Negative	5° 20′
Carbonate of Lead	Negative	10° 35′
Arragonite	Negative	18° 18′
Borax	Positive	28° 42′
Sugar	Negative	50°
Selenite	Positive	60°
Rochelle Salt	Positive	80°

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* The *principal axis* is, according to Sir D. Brewster, the middle point between the two nearest poles of no polarization.—*Phil. Trans.*, 1818.

Of the two rays produced by the double refraction of biaxial crystals, neither can be strictly denominated the *ordinary* one, since neither of them is refracted according to the ordinary law of single refraction. Both of them then are *extraordinary* rays, since they are refracted according to the laws of extraordinary refraction.

Another peculiarity of biaxial crystals is that the position of the optic axes is not constant, but varies in the same crystal, according to the colour of the intromitted ray and the temperature of the crystal. Thus a violet ray is separated into two pencils when incident in the same direction in which a red one is refracted singly. Sir John Herschel, to whom we are indebted for this discovery, found that the inclination of the resultant axes in Rochelle salt, is for violet light 56°, and for red light 76°, but in the case of nitre, the inclination of the axes for violet light is greater than for red light, and Sir D. Brewster discovered that glauberite has two axes for red light inclined about 5°, and only one axis for violet light. The changes produced on the inclinations of these axes by heat I shall hereafter have occasion to notice.

In conclusion, then, crystals considered with respect to their singly or doubly refractive properties may be thus arranged:

Optical Classification of Crystals.

CLASS 1.

Singly refracting crystals.

CLASS 2.

Doubly refracting crystals	*Order* 1. Uniaxial *Order* 2. Biaxial	either	*a.* Repulsive (negative) or *b.* Attractive (positive).

2. *Form of Crystals.*—A remarkable connection exists between the optical properties and the geometrical forms of crystals; and to this I have now to beg your attention.

A crystal, like every other solid, possesses length, breadth, and thickness; and the measures of these are three imaginary lines which pass through the centre of the crystal, and are termed the *axes.* They may be denominated *crystallographical* or *geometrical axes,* to distinguish them from the optic axes, with which they do not always coincide. Rose defines them to be "certain lines which pass through the centre of the crystal, and around which the faces are symmetrically disposed."

In some forms all these axes are equal in length, as in the cube; and in such cases it is said that the *axes are similar* or *alike.* Such crystals are termed *equiaxed.* But in a very large proportion of cases the axes are not all equal, and these crystals are said to be *unequiaxed.* Now it is a remarkable circumstance, that the equiaxed crystals are *single* refractors, while the unequiaxed are *double* refractors. This is the first fact demonstrative of the connection between the forms and the optical properties of crystals.

Of the unequiaxed crystals some have two, others three kinds of axes. If, for example, the length and the breadth of a crystal be alike, but the thickness different, the axes are of two kinds. Such crystals are usually said to have *two dissimilar axes,* but I shall term them *di-unequiaxed.* Other unequiaxed crystals have all their axes unequal; in other words, their length, their breadth, and their thickness are all unequal. Such crystals are generally said to have *three dissimilar* axes, but I shall call them *tri-unequiaxed.* Now, it is most remarkable that the di-unequiaxed crystals are double refractors, with *one* axis of [no] double refraction, while the tri-unequiaxed are double refractors with *two* axes of [no] double refraction. Here is another curious fact, illustrative of the relation which exists between the shape and optical properties of crystals.

Modern crystallographers arrange crystals in six groups, called *systems.* The equiaxed crystals constitute one system, called the *cubic, octohedral* or *tessular system.* The di-unequiaxed crystals comprehend two systems; one termed the *square prismatic* or *pyramidal system,* the other called the *rhombohedric* or *rhombohedral* *system.* The tri-unequiaxed crystals include three systems: one denominated the *right rhombic* or *rectangular prismatic system;* a second termed the *oblique rhombic* or *rectangular prismatic system;* and a third, called the *doubly oblique prismatic system.* The following table will, perhaps, render these statements more intelligible:

Geometrical Classification of Crystals.

		Systems.
Class 1. Equiaxed crystals (*single refractors*)	....	1. Cubic or Octohedral.
Class 2. Unequiaxed crystals (*double refractors*)	*Order* 1. Di-unequiaxed (*one axis of* [*no*] *double refraction*)	2. Square Prismatic. 3. Rhombohedric.
	Order 2. Tri-unequiaxed (*two axes of* [*no*] *double refraction*)	4. Right Rhombic Prismatic. 5. Oblique Rhombic Prismatic. 6. Doubly Oblique Prismatic.

I shall not at present enter into any further details respecting the geometrical peculiarities of each of these systems, as the subject will be more appropriately considered presently.

3. *Expansibility.*—Between the particles of matter there exist two classes of forces, the one attractive, the other repulsive. By the first, particles are approximated and united to form masses; by the second, they are separated to greater or less distances. Hence attraction and repulsion are antagonising forces.

Caloric or heat is a repulsive force. It augments the distance between particles and thereby weakens their attractive force; for molecular attraction rapidly diminishes as the distance between the particles increases. Hence solids and fluids, when heated, expand or dilate.

But the force of attraction which exists between the particles of different bodies (solids and liquids) varies considerably: in some being much greater than in others. Hence, the same amount of heat gives rise to a very different degree of expansion in different bodies. In other words, each solid or liquid has an expansion peculiar to itself, owing to the greater or less attractive force which exists between the molecules.

Some crystals, when heated, expand *equally* in all directions, and such I shall accordingly denominate *equiexpanding.* Now it is obvious that in these the existence of equally attractive forces in all directions must be inferred; and it is a curious and striking confirmation of this inference that crystals, which suffer equal expansion in all directions, are singly refracting and equiaxed.

A very large number of crystals, however, dilate, when heated, *unequally* in different directions; and such may be conveniently denominated *unequiexpanding.* In them expansion in one direction is accompanied in some, if not in all cases, with contraction in another direction; and it is, therefore, obvious, that the force of attraction between their particles must be unequal in different directions, the attractive or cohesive force being least in that direction in which the expansion is the greatest. Crystals of this class are doubly refracting and unequiaxed.

" Crystals which do not belong to the regular system expand unequally in the direction of their axes, by which the size of their angles changes." (Gmelin).

I apprehend that the unequal expansibility of crystals depends on the approach of the crystal to the fluid form, that is, to the spherical form; for, as Berthollet has observed, " the causes which determine the changes of constitution of bodies exercise an action the effects of which are evident before the changes of constitution have taken place." Three proofs of this may be stated.

1. Ice has a less sp. gr. than water at 32° F. Now, when water has been cooled down to 39° F., it expands on the further application of cold before it solidifies; so that the cause, whatever it may be, which renders ice lighter than water, is in operation before the water is frozen.

2. Sir Charles Blagden observed, that when salt is added to water, so as to lower the freez-

ing point, the approach to congelation is still shown by augmentation of volume.

3. When liquids are approaching their boiling points, they are gradually assuming the elastic state by progressive dilatation.

4. When heat is applied to solids, their forms begin to assume those nearest the sphere.

" After I had obtained," says Mitscherlich, " these results, that the expansion of crystals depended on the axes, and that calc spar suffered a greater expansion in the direction of the smaller axis, also according to the directions in which the atoms lie next, I sought to determine what influence the relative size of the axis had on the expansion. I, therefore, selected the combinations of carbonic acid with three isomorphous bases, lime, protoxide iron, and magnesia."

The changes produced on the angles of crystals for 180° F. were as follows:

Iceland Spar -	- 8′ 34½″
Bitter Spar -	- 4′ 6″
Ditto of Pfitschlat -	- 3′ 29″
Carbonate of Iron -	- 2′ 22″

Of these rhombohedra that of bitter spar of Pfitschlat was the most obtuse, that of Iceland spar the most acute.

Mitscherlich's Conclusions are as follows:

1. That the crystals which belong to the

regular system, as the spinelle and blende, show no double refraction, expand equally in all directions, and suffer no change in their angles. Hence the matter in them must be all equally arranged, and relates itself in every direction equally to light.

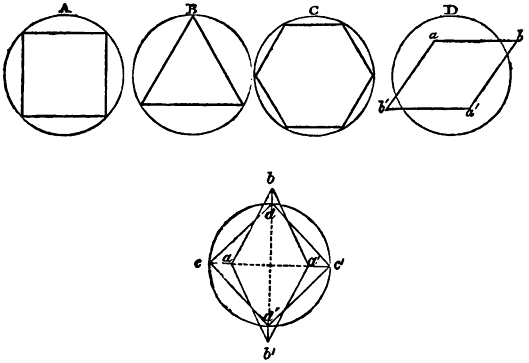
2. That the crystals whose primitive form is a *rhombohedron* or *six-sided prism* relate themselves differently to heat in one direction, that of their principal axis, than in other directions. Iceland spar, for example, expands in the principal axis (that is, the line which joins the two blunt angles of the rhombohedron) differently to that of the secondary axes, which are perpendicular to the principal one. Among the secondary axes the expansion is equal, and hence it follows that crystals with one axis of double refraction relate them to heat as to light.

3. That the crystals whose primitive form is a *rectangular octohedron*, a *rhombic octohedron*, or any of the crystals which have two axes of double refraction, expand unequally in all those directions.

4. That the expansion of crystals is determined strictly according to the axes; and as these are connected with the optical characters, so these have a determinate relation, so that the smaller axes expand comparatively more than the larger.

The essential difference in shape between an equiexpanding and an unequiexpanding crystal is, that the first can be inscribed within a sphere, the second cannot. We may rudely illustrate this in the lecture-room by diagram, substituting planes for solids, by inscribing a square, or an equilateral triangle in a circle (*fig.* 54., A and B). The first will represent the face of a cube, the second that of the regular tetrahedron. Now, it will be perceived that the circumference of the circle passes through all the angular points of the figure about which it is described. All these forms are equiexpanding.

Fig. 54.



The regular six-sided prism expands unequally in some directions, but equally in others. If now we describe a circle around the terminal faces, it will be perceived that it passes through all the angular points of this face (*fig.* 54., C), and in all directions, in this plane, the crystal expands equally. The rhombohedron cannot be inscribed within the sphere, because its axes are unequal. If, for example, we attempt to describe a circle around the rhombic face of Iceland spar (*fig.* 54., D), it will be found that while the obtuse angles (*a a′*) are contained within the circle, the acute ones (*b b′*) project beyond it. Now, under the influence of heat, this face expands in the direction of the shortest axis, but contracts in that of the longest axis, by which the rhomb approaches to the square, the obtuse angles becoming more acute, the acute ones more obtuse (*fig.* 54., E).

These illustrations will serve to give some general notions of the relations which exist between the forms and expansibilities of crystals.

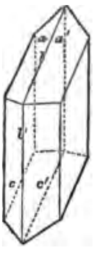
The *di-unequiaxed* crystals — that is, the doubly-refracting crystals, which have only one axis of [no] double refraction — expand equally in the direction of the equal crystallographical axes, but differently in that of the remaining one; and we may, therefore, denominate them *di-unequiexpanding crystals.* If, for example, a rhombohedron of Iceland spar be subjected to heat, it expands in the direction of its shortest axis, but contracts in all directions perpendicular to this, and in an intermediate direction it neither dilates nor contracts. Thus, according to Mitscherlich and Dulong, when heated from 32° to 212° F., it actually expands, in the direction of the shorter axis, 0·00286, and contracts in a direction perpendicular to this 0·00056; so that its apparent or relative expansion in this axis is 0·00342 (that is, 0·00286 + 0·00056). Now a necessary consequence of this unequal expansion is an alteration in the angles of the crystal: the obtuse ones become more acute, the acute ones more obtuse. In other words, the rhombohedron approximates to the cube; and in proportion to this change of form is the diminution of doubly refracting energy. Mitscherlich had conjectured that the latter effect would take place, and Rudberg has verified the conjecture. The last-mentioned philosopher found, that while the ordinary refraction of Iceland spar underwent little or no change, the extraordinary refraction was considerably diminished by an augmentation of temperature.

In *bitter spar* the obtuse angles of the primitive rhombohedron are lessened by heating it to 212°, by about 4′ 6″; and in *pure iron spar* to 2′ 22″. As of these minerals *calc spar* was the least obtuse, and ferruginous bitter spar the most obtuse rhombohedron, it follows that the expansion in the direction of the principal axis is not in the ratio in which it is shorter. (*Mitscherlich.*)

+	Total expansion of Iceland spar	0·001961 (by experiment).
—	Expansion in the axis	0·00342
	Contraction in the long axis	0·00056
—	Actual expansion in the axis	0·00286 (calculated).
+	Calculated total expansion	0·001737

The *triunequiaxed* crystals expand, when heated, unequally in the direction of all their axes, and, therefore, they may be denominated *uni-unequiexpanding crystals.* When *Arragonite* was heated from 32° to 212° the inclination of the lateral faces was augmented about 2′ 46″, and that of the terminal faces lessened about 5′ 29″ (Mitscherlich): and according to Fresnel *gypsum* expands more in the direction of its principal axis than in that of the two lateral ones (Gmelin). When the temperature of selenite is augmented, the inclinations of all its faces suffer changes. Thus, according to Mitscherlich, by heating it from 32° to 212° the inclination of the faces *c c′* was altered 10′ 50″, that of the faces *a a′* 8′ 25″, and that of the edges *b b′* only 7′ 26″.

Fig. 55.



Crystal of Selenite.

I have already explained what is meant by the terms *positive* or *attractive*, and *repulsive* or *negative* axes. They refer to optical differences in crystals, for which we find no corresponding geometric or crystallographical differences. Now there have been observed, in the effects of heat on crystals, differences analogous to the optical ones just referred to. Thus, in crystals with a repulsive or negative axis, as Iceland spar, expansion is greatest in the direction of the shortest axis, showing that the molecular attraction in this direction is the weakest; whereas in positive or attractive crystals, as selenite, heat produces less dilatation in a direction parallel to the axis than in a direction perpendicular to it.

"The inclination of the optic axes, in biaxial crystals," says Mr. Lloyd, "is a simple function of the elasticities of the vibrating medium in the direction of three rectangular axes, and the plane of the optic axes is that of the greatest and least elasticities. If, then, these three principal elasticities be altered by heat in different proportions, the inclination of the axes will likewise vary; and if, in the course of this change, the difference between the greatest elasticity and the mean, or between the mean and the least, should vanish and afterwards change sign, the two axes will collapse into one, and finally open out in a plane perpendicular to their former plane. All these variations have been actually observed. Professor Mitscherlich found, that in sulphate of lime the angle between the axes (which is about 60° at the ordinary temperature) diminishes on the application of heat; that, as the temperature increases, these axes approach until they unite; and that, on a still further augmentation of heat, they again separate, and open out in a perpendicular plane. The primitive form of the crystal undergoes a corresponding change, the dilatation being greater in one direction than in another at right angles to it. Sir David Brewster has observed an analogous and even yet more remarkable property in Glauberite. At the freezing temperature this crystal has two axes for all the rays of the spectrum, the inclination of the axes being greatest in red light and least in violet. As the temperature rises the two axes approach, and those of different colours unite *in succession;* and at the ordinary temperature of the atmosphere the crystal possesses the singular property of being *uniaxial* for violet light and *biaxial* for red. When the heat is further increased, the axes which have united open out in order, and in a plane at right angles to that in which they formerly lay, and, at a temperature much below that of boiling water, the planes of the axes for all colours are perpendicular to their first position.[*] The inclination of the optic axes in topaz, on the other hand, *augments* with the increase of temperature, and the variation, M. Marx has observed, is much greater in the coloured than in the colourless varieties of this mineral.[†]"

In conclusion, then, crystals considered with reference to the effects of heat on them may be thus arranged: —

Thermotic Classification of Crystals.

CLASS 1.

Equiexpanding crystals *(single refractors, equiaxed).*

CLASS 2.

Unequiexpanding crystals *(double refractors, unequiaxed)*
- *Order* 1. Di-unequiexpanding *(one optic axis, di-unequiaxed).*
- *Order* 2. Tri-unequiexpanding *(two optic axes, tri-unequiaxed).*

4. *Atoms or Molecules.* — It has been correctly stated by Sir D. Brewster[‡], that the polarizing or doubly refracting structure of crystals must "depend on the form of their integrant molecules, and the variation in their density." A few observations on the atoms or molecules of crystals will not, therefore, be out of place on the present occasion.

Like all other aggregates, crystals are made up of certain small parts conventionally called

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[*] *Edin. Trans.*, vol. xi.; and *Phil. Mag.*, 3rd series, vol. i., p. 417.

[†] *Jahrb. der Chemie*, vol. ix.

[‡] *Phil. Trans.* for 1818, p. 264.

atoms or *molecules.* It is unnecessary to discuss the question of their finite or infinite divisibility; and, to obviate the necessity of this, I shall assume, with Dumas*: that an atom is the smallest particle of a body which by mere juxtaposition with the particles of other bodies gives rise to a combination. Hence, therefore, the small parts of any one body which combine chemically with certain small parts of another body, without suffering further division, are what we understand by the terms *atoms* or *molecules.*

As these small parts or atoms are invisible, even when we aid the eye by the most powerful microscope, it is obvious that all observations on their size and shape must be speculative. Two opinions, however, have prevailed with respect to their form; Haüy and others have adopted the notion of their *angular* shape, while Hooke, Wollaston, and other more recent writers, assume them to be *rounded.* If we were to deduce the form of the molecules from that of their aggregates, we should adopt the angular hypothesis; for the most minute fragment of a crystal which we can procure and see, is angular. On the other hand, the spheroidal form of the planetary bodies, the tendency which liquids manifest to assume the spherical shape, and the mechanical facilities which the hypothesis of rounded atoms offers in the grouping of the atoms, have led later writers to adopt almost exclusively the views of Hooke and Wollaston.

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* *Traité de Chimie,* t. i. p. 33., 1821.

But it may be asked, Is the shape of an atom constant? or can it suffer change? May not the atoms of liquids be spherical or ellipsoidal and those of crystals angular? Ellipsoidal forms become angular by compression; and hence may not the ellipsoidal atoms of a liquid become angular in the act of crystallization? The idea has not, to my knowledge, occurred to crystallographers, but it appears to me that the subject well deserves consideration.

A spheroid is said to be *oblate* when, as in the case of the earth, the shortest diameter is its axis of revolution, but it is *prolate* or *oblong*, when the longer diameter is its axis of revolution. Now the shorter diameter may be regarded as the direction of the greatest attraction, or of compression, while the longer diameter is the direction of least attraction or of dilatation. In the case of the earth it is well known that gravity is greater at the poles than at the equator, a body weighing about $\frac{1}{194}$th more at the former than at the latter. It might, therefore, be supposed that crystals with one positive or attractive axis of double refraction would be formed of oblate spheroids, while those with one negative or repulsive axis would be made up of prolate spheroids.

But an objection exists to this hypothesis. According to it, *obtuse* rhombohedra ought to have one *positive* axis, while *acute* rhombohedra should have one *negative* axis of double refraction. Now the crystalline form of Iceland spar is an obtuse rhombohedron, but the optic axis of this substance is negative, so that its crystalline form is that which is produced by an oblate spheroid, while its optical property is that of a prolate spheroid. To obviate this objection, Sir D. Brewster * suggests that the molecules have the form of oblate spheroids, whose polar is to their equatorial axis as 1 to 2·8204, and that they were originally more oblate, but have been rendered less so by the force of aggregation, which dilated them in the direction of the smaller axis.

In point of fact, however, this assumption does not entirely obviate the difficulty, as the spheroids are still supposed to be oblate, though their axis is a negative one; and it appears probable that the same force which would render the axis negative should change the shape of the spheroid from the oblate to the prolate. Moreover, Sir D. Brewster's explanation involves the improbable supposition, that the original very oblate spheroids, if "placed together without any forces which would alter their form," would "compose a rhombohedron with a greater angle, and having no double refraction."

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* *Phil. Trans.*, 1830.

On the assumption that the axes of the atoms of crystals bear the same relations to each other that the axes of the systems of crystals themselves do, I have drawn up the following table of the supposed shapes of the atoms:

Table of the Shapes of the Atoms of Crystals.

			Systems of Crystals.
Ellipsoids.	CLASS 1. Equiaxed *(spheres)*		1. Cubic.
	CLASS 2. Unequiaxed	*Order* 1. Two equal axes *(spheroids)*	2. Rhombohedric. 3. Square Prismatic.
		Order 2. Three unequal axes	4. Right Prismatic. 5. Oblique Prismatic. 6. Doubly Oblique.

The doubly refracting structure is not inherent in the molecules themselves. Quartz or crystallized silica doubly refracts; but tabasheer, opal, and melted quartz, all siliceous substances, do not. Ice doubly refracts, while water singly refracts. What is the reason of this?

It will be generally admitted, I presume, that the double refraction of ice is a molecular property, and is associated with the shape of the atom; and hence, if the atoms of water have the same form as those of ice, they ought also to possess the doubly refracting property of the latter. Now, the advocates for the hypothesis of the unchangeability of atomic forms contend, that in ice the atoms are symmetrically and regularly arranged, with their axes pointing in the same direction; while in water they are unsymmetrically or irregularly arranged or jumbled together in such a manner that their axes have every possible direction, so as to create a general equilibrium of the polarizing forces. But, if this were the case, two specimens of water would scarcely ever present the same optical properties. If, by any accident, the axes of a large majority of the molecules should happen to be arranged in the same direction, the liquid would then possess a doubly refracting property. Now, it appears to me, that no hypothesis can be correct which ascribes to accident or chance a constant and invariable property of a body; for I hold, that, except when approaching the freezing point, liquid water is invariably a single refractor.

But, on the assumption that the shapes of atoms are, to a certain extent, capable of change, the difficulty is easily obviated. Suppose the atoms of liquid water to be spheres, and that in the act of freezing they become spheroids, the expansion of water in the act of freezing, the doubly refracting property, and the crystalline form of ice would then be readily explicable.

A consistent explanation of Dimorphism can scarcely be offered except on the assumption of the changeability of the shapes of the atoms. Carbonate of lime, for example, crystallizes in two distinct and incompatible forms, the one belonging to the rhombohedric, the other to the right prismatic system. In the first case, we call it Iceland spar; in the other, Arragonite. Iceland spar has one negative optic axis, Arragonite has two negative optic axes. The shapes of the atoms of these bodies must, therefore, be different. Admit that, under certain circumstances, the atom of carbonate of lime can change its shape, and all difficulty as to the production of these forms is at an end.

We suppose, therefore, that "when, in the process of evaporation or cooling, any two molecules are brought together by the forces or polarities which produce a crystalline arrangement, and strongly adhere, they will mutually compress one another." If the compression in three rectangular directions be equal, the crystal will be a singly refracting one: if the compression in two directions be equal but different in the third, the crystal will be a doubly refracting one with one optic axis: and, lastly, if the compression be different in each of the three directions, the crystal will doubly refract, and have two optic axes.

5. *Molecular Forces.* — Between the molecules of crystals, as well as of other bodies, there exist attractive and repulsive forces, in virtue of which the molecules are retained, not in contact, but within certain distances of each other. These forces are antagonists, and, therefore, the molecules acting under their influence take up a position of equilibrium, where the two opposing powers counterbalance each other.

But in crystals it is necessary to admit, besides ordinary *attraction* and *repulsion*, a third molecular force called *polarity*, which may be regarded either as an original or a derivative property. Without this it is impossible to account for the regularity of crystalline forms. Under the influence of a mutually attractive force particles would adhere together and form masses; the shapes of which, however, would be subject to the greatest variety; and though occasionally they might happen to be regular, yet this could not constantly be the case.

The simplest conception we can form of polarity is that it depends on the unequal action of molecular attraction or repulsion in different directions. A molecule endowed with unequal attractive forces in different directions may be said to be possessed of polarity.

A crystal has length, breadth, and depth or thickness. It is composed of molecules accumulated in three different directions corresponding to these three measurements; and it is obvious, therefore, that to account for their cohesion we must suppose that they attract each other in three directions; moreover, as the relative intensity of their attraction in these directions is, in many cases, unequal, it might be even supposed that they are three different kinds of attractions. To render this subject intelligible I shall make use of some illustrations employed by Dr. Prout in one of the Bridgewater Treatises.

Fig. 56.

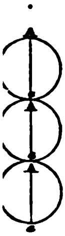


Fig. 57.

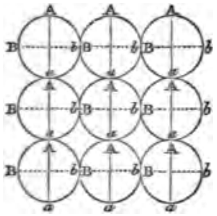
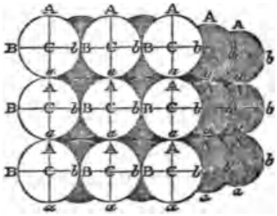


Fig. 58.



Suppose three molecules to adhere together to form a single *row,* line, or string of molecules, in virtue of an attractive force which I shall distinguish by the name of the *length force.* The points A A A or *a a a* are supposed to mutually repel each other, while A*a* A*a* A*a* mutually attract (*fig.* 56.).

Let us further suppose that three such rows of particles cohere in virtue of an attractive force acting in a direction perpendicular to the first. We may distinguish this as the *breadth force.* The points B B B or *b b b* are supposed to mutually repel, while B*b* B*b* B*b* mutually attract. These three rows of particles by their cohesion form a *plane* (*fig.* 57.).

Again, let us assume that three such planes cohere together, in virtue of an attractive force acting in a direction perpendicular to both the other forces. This force we may denominate the *depth force.* The points C C C or *c c c* are assumed mutually to repel, while C*c* C*c* C*c* mutually attract. These three planes by their union form a *solid* (*fig.* 58.).

Thus, then, we suppose that the molecules of crystals have three rectangular axes of attraction, or " lines along which they are most powerfully attracted, and in the direction of which they cohere with different degrees of force."

Though, for convenience and facility of explanation, I have employed the terms length-force, breadth-force, and depth-force, I by no means wish you to suppose that I adopt the notion of the distinct nature of these forces.

They may be, perhaps they are, one force acting in three directions.

These forces may be *equal* or *unequal*, and in the latter case two only, or all three may be unequal. That is, in some crystals the length-force may be equal to the breadth-force, and this to the depth-force. Or two only of the forces may be equal, the third being unequal: or, lastly, all three may be unequal.

As I have already had frequent occasion to speak of the *elasticity* of crystals, and as I shall again have to refer to it, I think it proper to explain what is meant by it. I have stated that the molecules of bodies are not in actual contact, but are separated by greater or less intervals. They are kept from actual contact, to which attraction urges them, by repulsion, while their further separation is opposed by attraction.

Now, we may disturb their state of equilibrium. We may, for example, by some compressing force, compel the particles to approach nearer to each other; but when the disturbing cause ceases to act, the particles after a few oscillations take up their original position. This then is what we mean by elasticity, which is obviously a consequence of attraction and repulsion. An elastic body is one which has the property of restoring itself to its former figure after any force which has disturbed it is withdrawn.

If by any force we approximate the particles of an elastic body, we augment its elasticity, and *vice versâ.* Now, as it is repulsion which opposes the approximation of particles, it appears that it is this force principally which confers on bodies the property called elasticity.

In some crystals their elasticity is equal in three rectangular directions. Such crystals may be denominated *equielastic.* Others, however, have unequal elasticities in different directions, and may be termed *unequielastic.* The first are single refractors, the latter are double refractors. Of the unequielastic crystals, some have two of their three elasticities equal, others have all three of their elasticities unequal: the first may be termed *di-unequielastic* — the second, *tri-unequielastic.*

The elasticity in the crystallographical axis may fall short of or exceed that in other directions: in the first case, crystals are said to have a negative or repulsive axis, or an axis of dilatation; in the latter case, they are said to have a positive or attractive axis, or an axis of compression.

By experiments made by Savart *, on the mode of sonorous vibration of crystalline substances, it has been shown, that the negative or repulsive axis is the axis of least elasticity, while the positive or attractive axis is the axis of greatest elasticity. " In carbonate of lime," he observes, " it is the small diagonal of the rhombohedron which is the axis of least elasticity, whilst it is that of greatest elasticity in quartz." To be convinced of the accuracy of this assertion, it is sufficient to cut, in a rhombohedron of carbonate of lime, a plate taken parallel to one of its natural faces, and to examine the arrangement of its two nodal systems, one of which consists of two lines crossed rectangularly, which are always placed on the diagonals of the lozenge, the primitive outline of the plate; and the other is formed of two hyperbolic branches, to which the preceding lines serve as axes (*fig.* 59.), but with this peculiarity, that it is the small diagonal which becomes the first axis of the hyperbola, whilst

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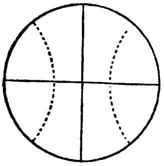
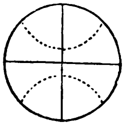
* Taylor's *Scientific Memoirs*, vol. i.

Fig. 59.



Nodal Systems of Calc Spar.

Fig. 60.



Ditto of Quartz.

it is its second axis in the corresponding plate of rock crystal (*fig.* 60.).

The following table shows the relation between the elasticities and shapes of crystals:

Table of the Elasticities of Crystals.

		Systems.		
CLASS 1. Equielastic crystals		1. Cubic.		
CLASS. 2. Unequielastic crystals	*Order* 1. Di-unequielastic	2. Rhombohedric 3. Square Prismatic	Elasticity in crystallographical axis, either	*a.* Minus (negative or repulsive) or *b.* Plus (positive or attractive).
	Order 2. Tri-unequielastic	4. Right Prismatic 5. Oblique Prismatic 6. Doubly Oblique Prismatic		

Conclusions.—From the preceding remarks it will appear,

1. That *singly refracting crystals* are equiaxed, equiexpanding, equielastic, and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of spherical atoms.

2. That *doubly refracting crystals* are unequiaxed, unequiexpanding, unequielastic, and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of either spheroidal atoms or ellipsoids with three unequal axes.

3. That *uniaxial crystals* are di-unequiaxed, di-unequiexpanding, di-unequielastic, and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of spheroidal atoms.

4. That *biaxial crystals* are tri-unequiaxed, tri-unequiexpanding, tri-unequielastic: and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of ellipsoids having three unequal axes.

5. That doubly refracting crystals, having a *negative* or *repulsive axis*, expand more, and have less elasticity in the direction of the axis than in directions perpendicular to this.

6. Lastly, that doubly refracting crystals, having a *positive* or *attractive* axis, expand less, and have more elasticity in the direction of the axis than in directions perpendicular to this.

I shall now go through the six systems of crystals, separately pointing out the most important of their optical and other properties.

SYSTEM I.

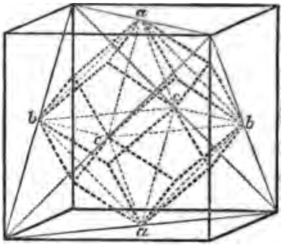
THE CUBIC OR OCTOHEDRAL SYSTEM.

Synonymes. — The *regular*, the *tessular*, the *tesseral*, or the *isometric system.*

Forms. — The forms of this system are either *homohedral* or whole forms, or *hemihedral* or half forms.

Homohedral Forms.	*Hemihedral Forms.*
1. Regular Octohedron.	1. Tetrahedron or Hemioctohedron.
2. Cube or Hexahedron.	2. Hemicositetrahedron or Pyramidal Tetrahedron.
3. Rhombic Dodecahedron.	3. Hemitriakisoctohedron.
4. Icositetrahedron.	4. Hemihexakisoctohedron.
5. Triakisoctohedron.	5. Hemitetrakishexahedron or Pentagonal Dodecahedron.
6. Tetrakishexahedron.	6. Hemioctakishexahedron.
7. Hexakisoctohedron.	

Fig. 61.



Four Forms of the Cubic System; viz., Cube, Regular Tetrahedron, Rhombic Dodecahedron and Regular Octohedron.

a a, *b b*, *c c*, The three rectangular equal axes.

Crystals. — Of the fifty-five or fifty-six simple or elementary bodies which have been hitherto discovered, the crystalline forms of not more than eighteen have been ascertained. Of this number, no less than thirteen are referable to the cubic system, namely *bismuth, copper, silver, gold, platinum, iridium* (?), *iron, lead, titanium, mercury, sodium, phosphorus* and *diamond.* Now, it appears *à priori* probable that simple bodies would have spherical atoms, and, therefore, the fact that the above-named substances crystallize in forms belonging to the cubic system, has been adduced as an additional evidence of their simple nature.

A considerable number of binary compounds also belong to this system — as the *chlorides of* *sodium*, *potassium*, and *silver*; *sal ammoniac;* the *bromide* and *iodine of potassium; fluor spar*, and the *sulphurets of zinc* (blende), *lead* (galena), *silver*, and *iron* (pyrites).

Some substances which contain more than two elements, also belong to this system, as *alum* and *garnet.*

Now, if the cubical form be an argument for the simple nature of the metals, why, it may be asked, do so many compound bodies present the same form? To this we can offer no satisfactory reply; and I think, therefore, we may conclude, with Dr. Wollaston, "that any attempts to trace a general correspondence between the crystallographical and supposed chemical elements of nature must, in the present state of the sciences, be premature."

Properties. — The crystals of this system have the following properties:—They are equiaxed singly refracting, equiexpanding and equielastic. We assume their molecules to be spherical.

When examined in the polariscope they present no traces of colour.

Exceptions. — A few exceptions exist to some of the preceding statements; but they are probably more apparent than real.

1. Several crystals of this system, as the diamond, fluor spar, alum, and common salt,

sometimes exhibit traces of a doubly refracting structure. But this is ascribable to irregularities of crystallization, or to the operation of compressing or dilating forces.

2. *Boracite* (a compound of boracic acid and magnesia) crystallizes in the general form of the cube; the edges of which are replaced, and the diagonally opposed solid angles dissimilarly modified. Instead, however, of being merely a single refractor, as its shape would lead us to expect, Sir D. Brewster found that it was a double refractor, with one positive axis of double refraction in the direction of a line joining two opposite solid angles of the cube. So that, in point of fact, it possesses the properties of a rhombohedric crystal. We may, therefore, regard it as a rhombohedron, whose angles differ from a right angle by an infinitely small quantity.

3. *Analcime* or *cubizite* (hydrated silicate of alumina and soda) constitutes another remarkable exception to the general rule, that crystals of the cubic system are devoid of a doubly refracting structure. The most usual form of this crystal is the icositetrahedron. Now if we suppose, says Sir D. Brewster, its contained cube "to be dissected by planes passing through all the twelve diagonals of its six faces, each of these planes will be found to be a plane of no

double refraction or polarization." All intermediate portions doubly refract. From every other known doubly refracting crystal analcime differs in the circumstance, that all its particles do not equally possess the property of double refraction, those in the planes above mentioned being devoid of this power, and the others possessing it in proportion to the squares of their distances from these planes. It differs from unannealed glass in the fact that a change in its external form does not give rise to a change in its polarizing power; but each fragment possesses the same optical property, when it is detached from the mass, that it had when naturally connected with its adjacent parts. Analcime, therefore, is a complete optical anomaly.

It has been suggested, that these curious optical properties may depend on the presence of both a doubly and a singly refracting mineral; and the fact, that the large opaque crystals of analcime, found in the valley of Fassa in the Tyrol, are traversed by plates of apophyllite (a doubly refracting crystal), lends support to this hypothesis.

SYSTEM II.

THE SQUARE PRISMATIC SYSTEM.

Synonymes. — The *four-membered* or *two-*

and one-axed, the *pyramidal*, the *tetragonal*, or the *monodimetric system.*

Forms.—The forms of this system are either *homohedral* or whole forms, or *hemihedral* or half-forms.

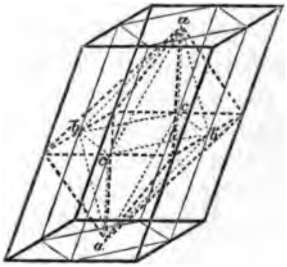
Homohedral Forms.

1. Octohedron with square base.
2. Terminal Face or Horizontal Plane.
3. Square Prism (of two positions).
4. Dioctohedron or Eight-sided Pyramid.
5. Eight-sided Prism.

Hemihedral Forms.

1. Hemioctohedron or Tetrahedron.
2. Hemi-dioctohedron.

Fig. 62.



Four Forms of the Square Prismatic System; viz., Two Square Prisms in different Positions, and Two Octohedra with Square Bases.

a a, Principal axis. *b b*, *c*, *c*, Secondary axes.

Crystals.—Among the crystals* of this

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* Sowerby (*Ann. Phil.* xvi. 223.) mentions crystals of *Palladium* in the form of octohedra with a square base, and of symmetrical prisms.

system are *chloride of mercury* (calomel), *bicyanide of mercury*, *ferrocyanide of potassium* (yellow prussiate of potash), *peroxide of tin*, *copper pyrites*, *zircon*, and *apophyllite*.

Properties. — The crystals of this system have the following properties: — They are di-unequiaxed, doubly refracting with one optic axis, di-unequiexpanding, and di-unequielastic. We assume their molecules to be either prolate or oblate spheroids.

The two equal rectangular geometric axes of this system are called *secondary axes;* while the third or odd one, which may be greater or less than the others, is the *principal* or *prismatic axis*, or the *crystallographical axis*, or the *axis of symmetry*. The optical characters of this system are the following:—The crystals are doubly refracting, with optic axis, which coincides with the principal axis.

If a thin slice of a crystal of this system, cut perpendicularly to the principal axis, be placed in the polariscope, it presents a system of circular rings, with a cross, which is either black or white, according to the relative positions of the polarizer and analyzer.

Ferrocyanide of potassium (commonly called *prussiate of potash*) may be conveniently used to show these effects. As found in commerce it usually occurs in the form of truncated octohedrons having a square base. It should be split with a lancet in the direction of its laminæ, that is, perpendicularly to its principal axis. Plates of about a quarter of an inch or more in thickness serve for the polariscope. They present a cross, and a negative system of circular rings; but the yellow colour of the crystal affects the brilliancy of the tints.

Zircon (a compound of silica and zirconia) is valuable for optical purposes, on account of its being a *positive* uniaxial crystal. Hence if a plate of it, which gives a system of rings of the very same size as that produced by a plate of Iceland spar (a *negative* uniaxial crystal) be superposed over the latter plate, the one system of rings is completely obliterated by the other; and the combined system exhibits neither double refraction nor polarization.

I shall defer all explanation respecting the rings and cross of this system until I speak of Iceland spar (a crystal of the rhombohedric system).

Exceptions.—Some exceptions to the above-mentioned properties of the crystals of this system exist, and require to be noticed.

1. *Ferrocyanide of potassium* is subject to irregularities of crystallization; and certain specimens present a double system of rings, or, in other words, are biaxial. Certain uniaxial specimens give a positive system of rings.

2. *Apophyllite* or *Fisheye-stone* (a compound of silica, lime, potash, and water) possesses some remarkable properties. In the most common variety, that from Cipit in the Tyrol, the diameters of the rings are nearly alike for all colours — those of the green rings being a little less. Some specimens of apophyllite, called by Sir D. Brewster *tesselated apophyllite*, present, in the polariscope, a tesselated or composite structure, instead of the ordinary cross and circular rings. They will be described hereafter among the tesselated or intersected crystals.

SYSTEM III.

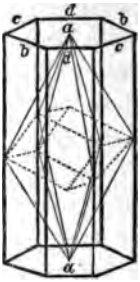
THE RHOMBOHEDRIC SYSTEM.

Synonymes.—The *three- and one-axed*, the *klinohedric*, the *hexagonal*, or the *trimetric system.*

Forms.—The forms of this system are either *homohedral* or *hemihedral.*

Homohedral Forms.	*Hemihedral Forms.*
1. Double Six-sided Pyramid (Hexagondodecahedron).	1. Rhombohedron (Hemidodecahedron).
2. Right Terminal Face (Horizontal Plane).	2. Scalenohedron.
3. Hexagonal Prism.	
4. Double Twelve-sided Pyramid (Didodecahedron).	
5. Twelve-sided Prism.	

Fig. 63.



Three Forms of the Rhombohedric System; viz., the Hexagonal Prism, the Scalene Dodecahedron and the Rhombohedron.

a a, The principal axis. *b b*, *c c*, *d d*, The secondary axes.

Crystals.—To this system belong some bodies supposed to be simple or elementary; viz., *antimony*, *arsenicum*, and *tellurium.*[*]

Plumbago or *graphite* and the *native alloy of iridium* and *osmium* also belong to this system.

Ice, magnetic iron pyrites, cinnabar, chloride of calcium, Iceland spar, carbonates of iron and zinc, dolomite (magnesian carbonate of lime), *nitrate of soda, hydrate of magnesia, tourmaline, talc, beryl, chabasite, quartz,* and *one-axed mica* belong to this system. And here it may be necessary to remark, that the substance known to mineralogists by the name of *mica*, and which, in trade, is usually but improperly termed *talc**, varies in its crystalline forms and optical properties. One kind crystallizes in regular hexagonal prisms, which cleave with extreme facility in one direction, viz., perpendicularly to their axis. This has only one axis of [no] double refraction, and consequently when a lamina of it is placed in the polariscope it presents only one system of circular rings traversed by a cross. This is the kind called *rhombohedral* or *uniaxial mica*, the majority of specimens of which have a negative or repulsive axis, though some have a positive or attractive one. But there is another kind of mica, of more frequent occurrence in the shops, and which is called by mineralogists *prismatic* or *diaxial mica*. It has two axes of double refraction, and consequently when a plate of it is placed in the polariscope, two systems of coloured rings are perceived. This kind of mica exists in two forms; one is crystallized in right prisms, the other in oblique prisms. Hence I shall distinguish the one as *right pris-*

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[*] Rose inserts "*Palladium(?)*" among rhombohedric crystals.

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* Talc is readily distinguished from mica by its greasy or unctuous feel. The most familiar kind of talc is that sold in the shops under the name of *French Chalk*. It is talc in an indurated earthy form.

matic mica, the other as *oblique prismatic mica.* They will be described hereafter. In conclusion, then, the kinds of mica may be thus arranged:

Mica...	Rhombohedric or Uniaxial	With a negative axis, or With a positive axis.
	Prismatic or Diaxial	Right Prismatic. Oblique Prismatic.

The principal constituents of mica are silica and alumina. But it also contains potash and sesquioxide of iron.

Properties.—The forms of this system possess four axes[*]; viz., three equal ones, called the *secondary axes*, placed in one plane, and crossing in the centre at an angle of 60°; and a fourth, termed the *principal axis*, or the *axis of symmetry*, or the *crystallographical axis*, perpendicular to the others, from which it differs in length. They are double refractors, with one optic axis coincident with the principal axis. They are di-unequiexpanding bodies, the expansion being different (greater or less) in the principal axis from that in the secondary ones. They are di-unequielastic; the elasticity in the principal axis being either more or less than that in the secondary axes. With regard to the atoms, we may assume their shape to be spheroids.

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[*] The description adopted in the lectures is that of Weiss and Rose; some other writers admit only three axes. Thus, Turner (*Elements of Chemistry* 7th ed., p. 588.) describes three equal but not rectangular axes; while Griffin (*System of Crystallography*, pp. 151. and 258.) admits three rectangular but unequal axes. Neither of these modes of description appear to me so completely to connect the form with the optical and other properties of the crystals as Weiss and Rose's method.

Iceland spar ($Ca\ O\ CO_2$) may be conveniently used to illustrate the optical properties of the crystals of this system. It occurs in rhomboidal masses, which by cleavage yield obtuse rhombohedra. The line which joins the two obtuse summits of one of these rhombohedra is called the *shortest* or *principal axis*, the *crystallographical axis*, the *axis of the rhomboid*, or simply the *axis*. A plane drawn through this axis, perpendicularly to a face of the crystal, is called the *principal section*. This section belongs rather to a face than to the entire crystal, for each face has its own. Now, when the incident rays are perpendicular to the face of the crystal, both the ordinary and extraordinary rays are always found in the same plane, so that the deviation of the extraordinary pencil takes place in the plane of the principal section. Every plane in the interior of the crystal, which is perpendicular to the axis, is called a *section perpendicular to the axis*, or the *equator of double* *refraction.* In this plane the doubly refracting force is at a maximum, and when a ray incident in this plane, the resulting extraordinary and ordinary rays are both in the same plane.

If a plate of Iceland spar, cut perpendicularly to the principal or shortest axis, be placed in the polariscope, the polarizing and analyzing plates being crossed, we observe coloured curves or concentric rings intersected by a rectangular black cross, the arms of which meet at the centre of the rings (*fig.* 64.).

Fig. 64.

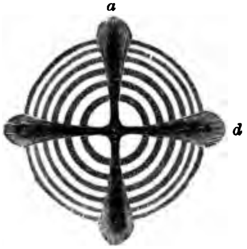


Fig. 65.

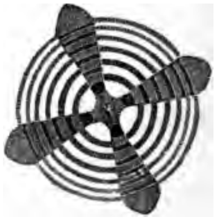
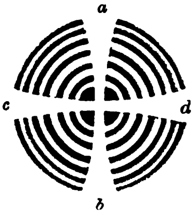


Fig. 66.



The coloured curves of rings are called *the* *lines of equal tint*, or *isochromatic lines* (from ἴσος *equal* and χρωματικὸς *coloured*). In this and other uniaxial crystals they are disposed in concentric circles, and are similar to Newton's rings seen by reflection.

If we revolve the plate of Iceland spar on its axis, the rings and cross preserve the same position; but if either the polarizing or analyzing plate be rotated, some remarkable changes occur.

Suppose the analyzing plate to be turned 45° round the incident ray in a left-handed direction, we observe that the original or primary coloured rings grow fainter or more dilute, and the cross seems to shift its position to the left, while its blackness lessens and is replaced by another set of rings, which alternate with and are complementary to, the original curves (*fig.* 65.).

If the analyzing plate be rotated 45° further in the same direction, that is, 90° to the first or original position, the black cross is replaced by a white one, and the original set of coloured rings is succeeded by a second or complementary set, the rings of which are intermediate to the original ones, and are similar to Newton's rings seen by transmission (*fig.* 66.).

If the system of rings with a black cross (*fig.* 64.) were superposed in the system with the white cross (*fig.* 66.), white light would be reproduced.

If the incident polarized light be white, the rings consist of compound tints produced by the superposition on each other of rings formed by each of the homogeneous rays composing white light. Of course, if the rings of all the colours were of the same size, the resulting system would consist of black and white rings; but being of different dimensions, we obtain a system of different colours. In this case, the cross is either black or white, not coloured.

If the incident polarized light be homogeneous the rings consist of rings of the colour of the light employed, separated by black rings. Thus, suppose red light to be used, the rings will be alternately red and black; whereas if blue light be employed, they will be alternately blue and black. Their size varies with the colour of the light: red produces the largest, violet the smallest system of rings. In all cases in which homogeneous light is employed, the cross is either a black or a coloured one.

The radii of the bright rings are as the square roots of the odd numbers, 1, 3, 5, 7, &c.; while those of the dark rings are as the square roots of the even numbers, 2, 4, 6, 8, &c. In other words, the squares of the diameters of the bright rings are as the odd numbers, 1, 3, 5, 7, &c.; while the squares of the diameters of the dark rings are as the even numbers, 2, 4, 6, 8, &c.

Square of the diameters of the ...	*Bright* rings	1	—	3	—	5	—	7	—
	Dark rings	—	2	—	4	—	6	—	8

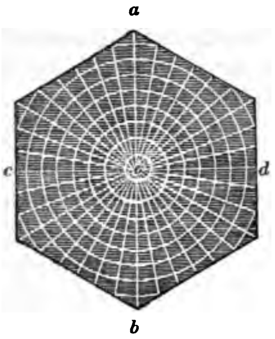
The actual diameter and breadth of the rings are increased by diminishing the thickness of the crystalline plate. To speak more precisely, the radii of the rings are inversely as the square root of the thickness of the plate; and, therefore, the rings are smaller with a thick plate than with a thin one. Thus, while a plate of a given thickness will produce a system of rings, the whole of which can be seen at once, a plate considerably thinner will give rings of so much larger diameter and greater breadth, that the whole system cannot be taken in at once by the eye. It is obvious, therefore, that the comparative doubly refracting power of two uniaxial crystals may be ascertained by observing the size of the rings produced by plates of equal thickness; with a powerful doubly refracting crystal the rings are less than with a crystal possessing this property in a weaker degree. In fact, the radii of the rings are inversely as the doubly refracting power of the crystal.

Let us now endeavour to explain generally the origin of the coloured rings and of the cross, according to the undulatory hypothesis; and, for precision and brevity of description, I shall suppose that tourmaline plates are used in the polariscope both for polarizing and analyzing.

The first tourmaline plate polarizes the light which is then incident on the Iceland spar. In their progress through the latter some of the polarized rays suffer double refraction, others are transmitted without undergoing this change. For there are two rectangular planes of polarization of the luminous rays in Iceland spar, one of the plane of polarization of the ordinary rays, the other of the extraordinary rays; and in those parts of the crystal in which the plane of polarization of the incident light coincides with either of the planes of polarization of the rays in the crystal, no double refraction occurs. On the other hand, in those parts of the crystal in which neither of its planes of polarization coincide with the plane of the incident polarized light, double refraction ensues.

All the ordinary rays which emerge from the crystal are polarized in planes which pass through the principal axis of the crystal: while the extraordinary rays will be polarized in planes perpendicular to these. Let *fig.* 67 represent the crystalline plate cut perpendicularly to the axis *e*. The radiating white lines represent the planes of polarization for the ordinary rays, and the circular white lines the planes of polarization for the extraordinary rays.

Fig. 67.

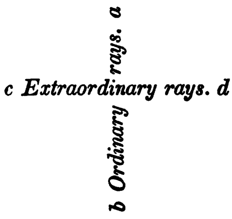


The two sets of rays (that is, the ordinary and the extraordinary) form two cones of refracted rays, having a common axis coincident with the axis of the crystal. The summit, or apex of each cone, will be at the eye of the observer; and the diameter of the base of the cone will of course vary according to its distance from the eye. The different rays, of which each cone is made up, undergo different changes. Those which form the axis of the cone traverse the plate at a perpendicular incidence, and, therefore, are not refracted; while those which pass through the plate obliquely, undergo double refraction.

The ordinary or the extraordinary rays forming the same cone have not all an equal intensity at different parts of its circumference. For if the plane of polarization of the incident light be identical with or parallel to *a b*, *fig.* 67., it is evident that, while the intensity of the ordinary rays will be at a *maximum* in the plane *a b*, and at a *minimum* or *nil* in a direction perpendicular to this *c d*, the intensity of the extraordinary rays will be at a *maximum* in the plane *c d*, and at a *minimum* or *nil* in a direction perpendicular to this, *a b*.

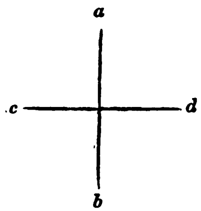
Hence those rays which are incident on the crystal in the plane *a b*, traverse the plate without having their plane of polarization charged, emerge as *ordinary* rays, and, by the subsequent action of the analyzing plate, form two arms of the rectangular cross, *a b* (*fig.* 67.). Those rays which are incident on the crystal at any point of the line *c d* also traverse the crystal without having their plane of polarization changed, but they emerge as *extraordinary* rays, and, by the subsequent action of the analyzer, form the remaining two arms of the rectangular cross *c d* (*fig.* 68.). The two sets of polarized incident rays which

Fig. 68.



thus traverse the crystal, without having their plane of polarization changed, and emerge, the one as the ordinary, the other as the extraordinary rays, form either a black or a white cross, according as they are either suppressed or transmitted by the second or analyzing tourmaline. If the two tourmalines be crossed the rays are suppressed—if they coincide the rays are transmitted. In the first case we perceive a black cross, in the second a white one.

Fig. 69.



Thus, then, all the rays which emerge from the second surface of the crystal, at any point of the two lines *a b*, *c d* (*fig.* 69.), will not be divided into two, nor have their planes of polarization altered. But all the polarized rays which are incident on the crystal in any direction intermediate between the positions *a b* and *c d* suffer double refraction, since their planes of polarization coincide neither with the plane of polarization of the ordinary, nor with that of the extraordinary rays; that is, the vibrations of the incident rays are resolved into two sets, one which forms the ordinary rays, and the other perpendicular to it, which forms the extraordinary rays. The two systems of waves produced by these two sets of vibrations proceed through the crystal with unequal velocities, and describe different paths; consequently they emerge in different phases, that is, in a condition for suffering interference by the action of the analyzer. In my last Lecture, however, I so fully explained the agency of the analyzer in giving rise to the phenomena of colour, that I need not now enter further into it. I shall, therefore, only add, that the coloured rings owe their origin to interference.

A circumstance which affects the formation of the rings, is the inclination of the polarized rays to the optic axis of the crystal. In the axis itself, where the arms of the cross pass athwart each other, no colour is produced, consequently there can be, in this position, no double refraction. But those rays which suffer double refraction and produce colour, traverse the crystal obliquely, and at an inclination to the optic axis, and the obliquity or inclination augments in proportion as we recede from the centre or axis. Now the effect of an increase in the inclination of the rays to the optic axis is equivalent to an increase of thickness in the crystals. Hence it is obvious why we have rings, and not a uniform tint, as in the case of the thin films of selenite described in our last Lecture. Moreover, it is obvious that at equal distances around the axis the inclinations will be the same, and consequently the similar tints will be found at equal distances from the axis; in other words, the lines of equal tint or isochromatic lines will be disposed in concentric circles.

That the tints of the system of rings accompanying the black cross should be complementary to those which accompany the white cross, will be readily understood from what was stated in the last lecture respecting the office of the analyzing plate.

The rings of the two systems do not occupy the same position, but are transposed; that is, the bright rings of the one system occupy the position of the dark rings of the other system. The cause of this obvious—the rings of the two systems are produced by different rays. The two sets of rays which successively pass through the tourmaline analyzing plate in its two positions, would, if this plate were not interposed, pass simultaneously and produce a uniform tint of the same colour as that of the incident light. In other words, without the analyzer neither cross nor rings would be perceived.

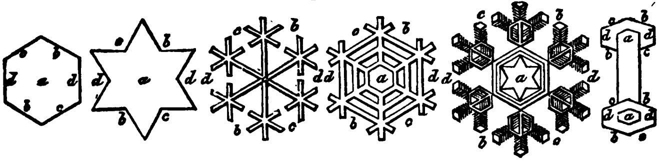
But why, it may be asked, is the maximum brilliancy of the rings at the middle of the four quadrants; that is, in lines or directions which are equidistant from the two nearest arms of the cross? Because, it may be replied, it is at these spots that the ordinary and extraordinary rays (produced by double refraction) are equal. On either side of these directions the ordinary ray has either a greater or less intensity than the extraordinary one.

Iceland spar has, as I have already stated, a negative or repulsive axis; and I shall take this opportunity of explaining the method used by Sir D. Brewster for distinguishing whether the axis of a crystal be positive or negative. Take a film of selenite (sulphate of lime), and mark on it the *neutral axes;* then, by a little wax, attach it to a plate of Iceland spar (cut so as to show the rings), and place them in the polariscope. If the film by itself produces the red of the second order, it will now, when combined with the Iceland spar, obliterate part of the red ring of the second order in two alternate and opposite quadrants (either *a c* and *b d*, or *a d* and *b c*, *figs.* 64. and 65.). The line of the film which crosses these two quadrants at right angles to the rings is the *principal axis* of selenite, and should be marked as such. Then if we wish to examine whether any other system of rings is positive or negative, we have only to cross the rings with the principal axis "by interposing the film: and if it obliterates the red ring of the second order in the quadrant which it crosses, the system will be negative; but if it obliterates the same ring in the other two quadrants which it does not cross, then the system will be positive. It is of no consequence what colour the film polarizes, as it will always obliterate the tint of the same nature in the system of rings under examination."

Plates of *tourmaline*, obtained by cutting the crystals at right angles to the principal or prismatic axes, as described in my first Lecture (*fig.* 24., p. 58.), present circular rings and a cross, when examined by the polariscope.

Ice belongs to the rhombohedric system. The beautiful and regular, though varied, crystalline forms of snow may be regarded as skeleton crystals of this system. I have here depicted (see *fig.* 70.) a few forms taken from Captain Scoresby's work on the Arctic Regions; and in them you may readily trace the three secondary axes (*b b*, *c c*, *d d*), placed in

Fig. 70.



Crystals of Snow.

the same plane, and inclined to each other at an angle of 60°, while the fourth or principal axis (*a a*) is perpendicular to the other three.

Now, if you take a sheet of clear ice, about an inch thick, and which has been slowly formed in still weather, and examine it by the polariscope, you will readily detect the circular rings and cross. The system of rings formed by ice is positive or attractive; and, therefore, is of an opposite kind to that of Iceland spar.

Exceptions. — To the general properties of crystals of the rhombohedric system some exceptions exist.

1. In Iceland spar, beryl, and other crystals of this system, the rings are not unfrequently distorted, owing to irregularities of crystalline structure.

2. *Quartz* belongs to this system, but its optical phenomena are very different to those of any other crystal, and will be described in my next Lecture.

3. *Amethyst* is another exception, which I shall hereafter describe.

4. *Chabasite* (a mineral compound of silica, alumina, lime water, and potash) is a rhombohedral crystal, sometimes endowed with remarkable optical properties. "In certain specimens of this mineral," says Sir D. Brewster, "the molecules compose a regular central

crystal, developing the phenomena of regular double refraction; but in consequence of some change in the state of the solution, the molecules not only begin to form a hemitrope crystal on all the sides of the central nucleus, but each successive stratum has an inferior doubly refracting force till it wholly disappears. Beyond this limit it appears with an opposite character, and gradually increases till the crystal is complete. In this case the relative intensities of the axes or poles from which the forces of aggregation emanate have been gradually changed, probably by the introduction of some minute matter, which chemical analysis may be unable to detect. If we suppose these axes to be three, and the foreign particles to be introduced, so as to weaken the force of aggregation of the greater axis, then the doubly refracting force will gradually diminish with the intensity of this axis, till it disappears, when the three axes are reduced to equality. By continuing to diminish the force of the third axis the doubly refracting force will reappear with an opposite character, exactly as it does in the chabasite under consideration."

SYSTEM IV.

RIGHT PRISMATIC SYSTEM.

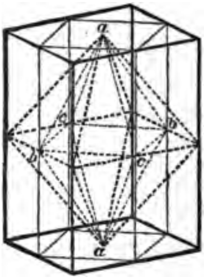
Synonymes. — The *right rhombic prismatic*, or *right rectangular prismatic system*, the *pris-*

matic system, the *two- and two-membered* or *one- and one-axed system*, the *orthotype system*, the *rhombic* or the *holohedric-rhombic system.*

Forms. — In this system are included the *right rhombic prism*, the *right rhombic octohedron*, the *right rectangular prism*, and the *right rectangular octohedron.* Rose enumerates the following forms as belonging to this system:

Homohedral.	*Hemihedral.*
1. Forms whose faces are inclined to all three axes (*Octohedra*).	Rhombic Tetrahedron.
2. Forms whose faces are inclined to two axes, but are parallel to the third (*Prisms*).	
3. Forms whose faces are inclined to one axis but are parallel to the two others (*Single Planes*).	

Fig. 71.



Right Rectangular Prism.
Right Rhombic Prism.

Right Rectangular Octohedron.
Right Rhombic Octohedron.

a, Principal or prismatic axis. *b b*, *c c*, Secondary axes.

Crystals.—The simple or elementary bodies which crystallize in forms belonging to this system are only three, namely, *iodine*, *native sulphur*, and *selenium*.

Among the binary compounds we have *pyrolusite* (binoxide of manganese), *white antimony* (sesquioxide of antimony), *bichloride of mercury*, *chloride of barium*, *orpiment*, and *grey antimony* (sesquisulphuret of antimony).

A considerable number of salts belong to this system, as the *carbonates of lead*, *baryta*, *strontian*, *potash*, and *ammonia;* the *bicarbonate of ammonia*, and that variety of carbonate of lime called *Arragonite;* the *nitrates of potash*, *ammonia*, and *silver;* the *sulphates of magnesia*, *zinc*, *baryta*, and *strontian*, and *bisulphate of potash; Rochelle salt* (tartrate of potash and soda) and *emetic tartar* (tartrate of potash and antimony).

To the above must be added the following substances: *topaz*, *dichroite*, *citric acid*, and *morphia*.

Properties.—The crystals of this system present the following properties:—They have three rectangular axes all of different lengths; they are doubly refracting with two optic axes, and are tri-unequiexpanding. Consequently they have three rectangular unequal elasticities. On the ellipsoidal hypothesis, their atoms are ellipsoids, with three unequal axes.

They present no crystallographical character by which the *principal axis* can be distinguished from the others called *secondary axes;* so that in a geometrical point of view the choice of this axis is altogether arbitrary. But considered optically the principal axis is the middle point between the two nearest poles of no polarization. It corresponds with what is called by Mr. Brooke the *prismatic axis;* that is, the axis which passes through the centres of the terminal planes of the prism.

If you examine one of the simple or primary forms of this system — say this unmodified rectangular prism (the outer prism of *fig.* 71.), you observe there is no single line around which the figure is symmetrical; nor any square plane, or plane which can be inscribed within the circle. But let each of the two opposite terminal edges be replaced by a square plane, both equally inclined to the prismatic axis, and the line which passes through the centre of each of these planes will represent the direction of one of the optic axes.

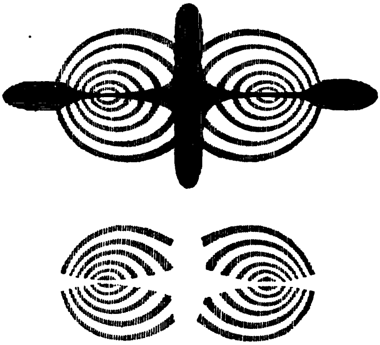
As the crystals of this system have two optic axes, they present, when examined by the polariscope, a double system of rings. In nitre, carbonate of lead, and Arragonite the inclination of these axes is small; and, therefore, both systems of rings may be seen at the same time.

In order to examine these by the polariscope, we must, in the case of the three crystals just mentioned, cut slices of them perpendicularly to the principal or prismatic axis. But in topaz, right prismatic mica, and Rochelle salt, the inclination of the optic axes is too great to permit both of them to be seen simultaneously; and, therefore, only one of them can be seen at a time. Consequently, if we examine by the polariscope, a plate of any of these crystals, cut at right angles to the prismatic axis, we must incline it first on one side and then on the other, to see successively the two systems of rings. To obviate this inconvenience, plates of these crystals should be prepared by grinding and polishing two parallel faces perpendicular to the axis of one system of rings.

Nitrate of potash, also called *nitre* or *saltpetre* ($N O_5 + K O$), is a very instructive crystal for illustrating the double system of rings. It is usually met with in the form of a six-sided prism, with diëdral summits.

For placing in the polariscope, we use plates of from $\frac{1}{12}$th to $\frac{1}{15}$th of an inch in thickness, cut perpendicular to the prismatic axis. If one of these be put in the polariscope in such a position that the plane passing through the optic axes is in the plane of primitive polarization, we shall then perceive a double system of coloured elliptical or oval rings, intersected by a cross; but the centre of the cross is equidistant from the centres of the two systems of rings, so that through the centre of each system passes one arm or bar of the cross, the other arm being at right angles to the former. When the polarizing and analyzing plates are crossed, we have a double system of coloured rings, with a black cross (*fig.* 72.); but when the polarizing and analyzing plates coincide, we have another double system of coloured rings, exactly complementary to the first, with a white cross (*fig.* 73.).

Figs. 72. and 73.



If when the analyzing and polarizing tourmaline plates are crossed, we revolve the plate of nitre in its own plane (both the tourmaline plates remaining unmoved) the black cross opens into two black hyperbolic curves. When the angle of rotation is a quarter of a right angle, we have the appearance represented by *fig.* 74.; when it equals half of a right angle, the black arms have assumed the forms of *fig.* 75.

Fig. 74.

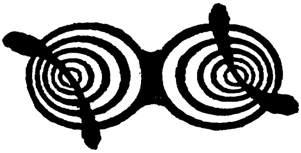
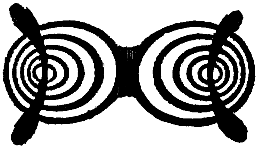


Fig. 75.



Here, then, is a remarkable distinction between biaxial and uniaxial crystals, for you will remember I demonstrated that when the uniaxial crystal was rotated in the polariscope, the black cross retained its position and shape.

The variation of form, as well as the general figure of the isochromatic lines, resembles the curve called by geometers the *lemniscate*. The inner rings encircle one pole only, but the outer ones surround both poles. The number of rings which surround both poles augments, as we diminish the thickness of the plate of nitre, until all the rings surround both poles, and the system thus greatly resembles, in appearance, the rings of a uniaxial crystal, from which, however, they are distinguished by their oval form.

I have already stated, that in biaxial crystals the optic axes for different colours do not coincide. In the case of nitre, the axes for red make with each other a smaller angle than the axes for blue. That is, the red ends of the rings are inward, or between or within the two optic axes, while the blue ends are outwards, or exterior to the two axes. But as the red rings are larger than the blue ones, it follows that there are points exterior to the axes where all the colours are mixed, or all are absent. At these spots, therefore, the rings are nearly white and black. Now, if we trace the same rings to the positions between the axes, " the red rings will very much over-shoot the blue rings; and, therefore, the rings have the colour peculiar perhaps to a high order in Newton's scale."*

If we attempt to illustrate the mode of formation of these rings in a way analogous to that pursued for the circular rings in uniaxial crystals (as at p. 209.), it will be easily apparent that no very simple or exact representation of that kind can be given on account of the light not being here symmetrical with regard to any one point. If we investigate the subject mathematically, the construction may, indeed, be readily made out, for which the reader is referred to Mr. Airy's Tracts, art. 163. : but it would be impossible to convey any distinct idea without going into the whole analysis. We may, however, give a sort of approximate representation of the case by means of the following figure, which corresponds to the one for uniaxial crystals in page 209. Here the curves represented are *very nearly*, but not accurately, *confocal ellipses* and *confocal hyperbolas*. *o o′*, the position of the optic axes, are the foci of all the ellipses and all the hyperbolas. These ellipses and hyperbolas are so described that they cut each other at right angles.*

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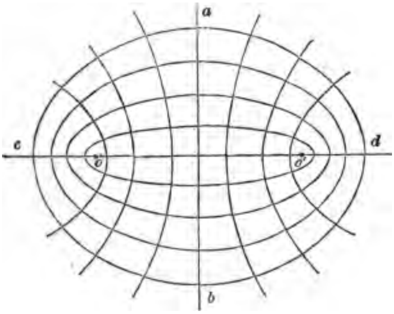
* Airy, *Mathematical Tracts*, p. 396. 2nd. ed. 1831.

Fig. 76.



When the optic axes coincide, the crystal becomes uniaxial, and the hyperbolas degenerate into the radiating lines in *fig.* 67. page 209., and the ellipses become the circles of the same figure.

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* This construction was communicated to the Author by a friend in Cambridge.

Native crystallized *carbonate of lead* constitutes a splendid polariscope object. It is to be cut like nitre; that is, perpendicularly to the prismatic axis. The optic axes are but slightly inclined (about 10½°), and, therefore, both of them may be simultaneously perceived. The systems of rings have a similar form to those of nitre, and, like the latter, the red ends of the rings are inwards, the blue ends outwards.

Arragonite forms an interesting polariscope object. It is identical in chemical composition with calcareous or Iceland spar, but differs in crystalline form: calcareous spar belonging to the rhombohedric, Arragonite to the right prismatic, system. According to Gustav Rose, both these forms of carbonate of lime may be artificially produced in the humid way, but calcareous spar at a lower, Arragonite at a higher, temperature. In the dry way, however, calcareous spar alone can be formed.

The inclination of the optic axes of Arragonite being small (about 18°) we can easily see, at the same time, the two negative systems of rings surrounding their two poles, but considerably more separated than in the case of nitre.

For this purpose, a plate of the crystal is to be cut perpendicularly to the prismatic axis, that is, equally inclined (at about 9°) on each of the optic axes. If we rotate the plate of Arragonite on its axis in the polariscope, the tourmaline plates being crossed and unmoved, the two sets of rings appear to revolve around each other. By superposing two plates of Arragonite, we obtain four systems of rings.

In *Rochelle salt* (tartrate of potash and soda), the optic axes of the differently refrangible or coloured rays are considerably separated. If a plate of this crystal, cut perpendicularly to the prismatic axis, be inclined first on one side and then on the other, both the systems of rings may be successively perceived. But to observe the separation of the axes for differently coloured rays, Sir J. Herschel directs the plate to be cut perpendicularly to one of its optic axes. If we view the rings with homogeneous light they appear to have a perfect regularity of form, and to be remarkably well defined. With differently coloured lights, however, they not only differ in size but in position. If the light be " alternately altered from red to violet, and back again, the pole, with the rings about it, will also move backwards and forwards, vibrating, as it were, over a considerable space. If homogeneous rays of two colours be thrown at once on the lens, two sets of rings will be seen, having their centres more or less distant, and their magnitudes more or less different, according to the difference of refrangibility of the two species of light employed."

Topaz (a fluosilicate of alumina) belongs to this system. As the inclination of its optic axes is great (about 50°), we can see at once only one of its two systems of rings. It slits with facility in planes perpendicular to its prismatic axis, and equally inclined to its two optic axes. If we take a plate cut perpendicularly to the prismatic axis, and incline it first on one side and then on the other, we shall see successively two systems of oval rings, which have been very elaborately described by Sir D. Brewster.

The plates of topaz sold in the opticians' shops, for polariscope purposes, have been obtained by cutting the crystal perpendicularly to one of the optic axes; that is, at an angle of about 25° to the prismatic axis. With these we only see one system of nearly circular rings traversed by a bar or arm of the cross. We observe also, that the optic axes for different colours are somewhat separated; for the red ends of the rings are inwards, or within the resultant axes, while the blue ends are outwards.

The topazes which are cut for optical purposes come from Australia, and are technically known as *Nova Minas*. They are colourless, and remarkably free from flaws and macles.

Exceptions.— In this system, as in the others, we meet with exceptions to some of the statements above made.

1. Macled crystals, especially of nitre and Arragonite, are very common. Occasionally idiocyclophanous crystals of nitre are met with. These will be noticed subsequently.

2. *Sulphate of potash* is a tesselated or composite crystal, and such will be described hereafter.

3. Some specimens of *Brazilian topaz* are tesselated.

SYSTEM V.

OBLIQUE PRISMATIC SYSTEM.

Synonymes. — The *two- and one-membered system*, the *hemiorthotype system*, the *monoklinohedric system*, or the *hemihedric-rhombic system.*

Forms. — To this system belong the *oblique octohedron with a rectangular base*, the *oblique rectangular prism*, the *oblique octohedron with a rhombic base*, and the *oblique rhombic prism.* Mr. Brooke's *right oblique-angled prism* is referred to this system.

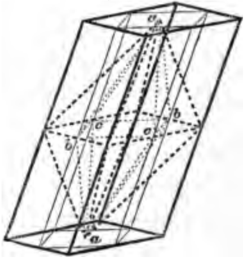
Rose makes no distinction between the homohedral and hemihedral forms in this system; but enumerates the following as the forms of the system:

1. Forms whose faces are inclined to all the three axes (*Octohedra*).

2. Forms whose faces are inclined to two axes, and are parallel to the third axis (*Prisms*).

3. Forms of which the faces are inclined towards one axis and parallel to the two others.

Fig. 77.



Oblique Rectangular Prism, Oblique Rhombic Prism, Oblique Rectangular Octohedron, and Oblique Rhombic Octohedron.

a, *a*, Principal or prismatic axis. *b b*, *c c*, Secondary axes.

Crystals. — To this system belong the crystals of *sulphur*, when obtained by slow cooling; *realgar* (red sulphuret of arsenic), and *red antimony* (native Kermes).

A considerable number of salts belong here also: as the *sulphates of soda*, *lime* (selenite), and *iron*; *carbonate* and *sesquicarbonate* (trona) *of soda*, *bicarbonate of potash*, *chlorate of pot-*

ash, phosphate of soda, borax (tincal), the *acetates of soda, copper, zinc* and *lead, binacetate of copper, binoxalate of potash, Glauberite* (sulphate of lime and soda,) and *chromate of lead.*

To this system are also referred *oblique prismatic mica* (one of the kinds of diaxial mica described by Count de Bournon), *tartaric* and *oxalic acids, sugar candy,* and the *crystals from oil of cubebs.*

Properties. — The forms of this system have three axes, all of which are unequal. Two of them cut one another obliquely, and are perpendicular to the third. From the forms of the preceding system they are distinguished by this obliquity of two of their axes. As the three axes are unequal, it is indifferent which we take for the *principal axis;* but one of the inclined axes is usually selected, because, in general, the crystals are extended in the direction of one of these, so that in most cases the faces which are parallel to this axis greatly predominate. This axis, therefore, corresponds with that which Mr. Brooke calls the *prismatic axis.* The other two axes are called *secondary axes,* the one which is oblique being termed the first secondary axis; the other, which is perpendicular to it, being denominated the second secondary axis.

The crystals of this system are doubly refracting with two optic axes. They are tri-unequiexpanding, and tri-unequiaxed. On the ellipsoidal hypothesis their atoms are assumed to be ellipsoids with three unequal axes.

In the opticians' shops, plates, cut from several crystals of this system, are sold for showing, in the polariscope, the systems of lemniscates. They are usually cut perpendicularly to one of the optic axes; and, therefore, show but one system of rings traversed by a bar. Of these I shall notice three.

Borax deserves especial notice, on account of its optic axes for the different homogeneous colours lying in different planes, a fact for the knowledge of which we are indebted to Sir John Herschel. As in other biaxial crystals it will be observed that the rings, or lemniscates, are traversed by only one bar or arm of the cross. In the next place it will be perceived, that the axes for red light make a greater angle with each other than the axes for blue or purple; hence, unlike nitre and carbonate of lead, the red ends of the rings are outwards, while the blue ends are inwards. This fact, however, only proves that the axes for different colours do not coincide: it does not show that they lie in different planes. But if, the tourmaline plates being crossed, the plate of borax be placed at such an azimuth that the bar or arm of the black cross distinctly traverses the centre of the system of lemniscates, and leaves an interval perfectly obscure, we shall then see that the arm of the cross is not straight, as in nitre (*fig.* 72.), but has a hyperbolic form. The reason of this difference is obvious: in nitre all the axes lie in the straight line or plane, while in borax they are disposed obliquely, or in different planes.

Selenite is sometimes cut to show one of its two systems of rings. I have already described this crystal, and demonstrated the uniform tints produced by films of selenite of equal thickness. To show the rings the crystal must be cut at right angles to one of its optic axes.

Sugar-candy makes an interesting polariscope object. This crystal is also cut perpendicular to one of its optic axes, and, therefore, shows only one of its two systems of rings.

Exceptions.—Owing to irregularities of crystallization, the rings of some of the crystals of this system are often seen more or less distorted. Macled selenite is very common, as I have before mentioned. Sir John Herschel states, that idiocyclophonous crystals of *bicarbonate of potash* are frequent. I shall hereafter notice them.

SYSTEM VI.

DOUBLY OBLIQUE PRISMATIC SYSTEM.

Synonymes. — The *one- and one-membered,* the *anorthotype,* the *triklinohedric,* or the *tetartohedric-rhombic system.*

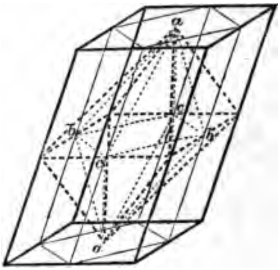
Forms. — To this system belong the *doubly oblique octohedron* and the *doubly oblique prism.* Rose makes no distinction of homohedral and hemihedral forms; but arranges the forms of this system as follows:

1. Forms whose faces are inclined to all the three axes. (*Octohedra*).

2. Forms whose faces are inclined to two axes, and are parallel to the third. (*Prisms*).

3. Forms which have their faces inclined towards one axis only. These forms are the faces of truncation of the three kinds of angles of the octohedron.

Fig. 78.



Two Doubly Oblique 'Prisms, and two Doubly Oblique Octohedra.

a a, The principal axis. *b b*, *c c*, The secondary axes.

Crystals.—The most important substances, whose crystalline forms are referable to this system, are *boracic acid, sulphate of copper**, *nitrate of bismuth, sulphate of cinchonia, quadroxalate of potash*, and *gallic acid.*

Properties.—The forms belonging to this system have three axes all unequal and oblique-angular to one another; they are doubly refracting, with two optic axes; and they are tri unequiexpanding. Consequently they have three unequal elasticities.

Of the three axes just referred to, one is taken for the *principal axis*, the other two for the *secondary axes;* but, geometrically considered, the selection is altogether arbitrary. The principal axis coincides with Mr. Brooke's *prismatic axis.*

"The forms of this system," says G. Rose, "have not symmetrical faces. All the faces are unique, so that this system is the one which differs the most from the regular or cubic system, in which we find the greatest symmetry, on account of the equality and perpendicularity of the axes." It is sometimes exceedingly difficult to distinguish the forms of this system. "The doubly oblique prism," observes Mr. Brooke, "will be found the most difficult of all the primary forms to determine from its secondary crystals. It is distinguishable from all other forms, when its crystals are single, by the absence of symmetrical planes analogous to those of other prisms; but it very frequently occurs in hemitrope or twin crystals, which must resemble some of the forms of the oblique rhombic prism, and can then be distinguished only by some re-entering angle or other character on the surface of the crystal."

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* Mr. Brooke (art. *Mineralogy* in the *Encyclopædia Metropolitana*), says, that the primary form of sulphate of copper is an oblique rhombic prism, and Mr. R. Phillips (*Translation of the Pharmacopœia*, p. 237., 4th edit., 1841) has adopted Mr. Brooke's statement. If this be correct, sulphate of copper of course belongs to the oblique prismatic system, and not to the doubly oblique prismatic system. I have, however, referred it to the latter system, on the authority of Gustav Rose, and most of the other eminent German crystallographers.

Sulphate of copper ($Cu\ O.\ S\ O_3.\ 5\ Aq.$) is sometimes cut to show the two sets of rings or lemniscates of this system; but the blue colour of the crystal destroys their brilliancy.

MACLES AND COMPOUND CRYSTALS.

I have now arrived at the last part of my subject, viz., the consideration of the optical properties of those remarkable crystalline structures commonly known by the name of *macles*, a term introduced into mineralogy by Romé de Lisle. Sometimes these structures appear to consist of one crystal, whose parts are transposed, dislocated, or displaced. When one-half of the crystal appears to have been turned partly round on an imaginary axis, passing through the centre of the crystal, and perpendicularly to the plane of section, and to have been united to the other half in this position, the body thus produced has been called the *hemitrope* (from ἡμι *half* and τρέπω *I turn*). Of this arrow-headed selenite is a familiar example. Sometimes two or more crystals are found intersecting each other, and are then called *intersecting crystals.* When two crystals are joined, they form the structure called a *twin* or *double crystal.*

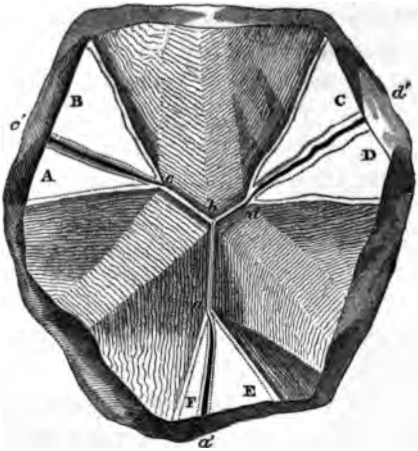
Many or most of the forms I have now referred to are irregular, and might appear to be accidental. But there are some others which have great regularity, and cannot be ascribed to accident. Such are some specimens of apophyllite and sulphate of potash. They constitute what Dr. Brewster has termed *tesselated* or *composite crystals;* the real structure of many of which is only discoverable by the aid of polarized light; they consist of several crystals, or portions of crystals, juxtaposed, or united so as to form a compound crystal, the figure of which is very different from that of the crystals composing it.

Macled crystals of *nitre* or *Arragonite* are very common, and frequently their precise structure is undiscoverable by the naked eye.

In *quartz* we often find right and left-handed crystals intersecting each other.

Amethyst (by many mineralogists considered to be a variety of quartz) is a remarkable example of a combination of right and left-handed varieties of quartz. If a plate of amethyst, cut perpendicularly to the principal axis of the crystal, be examined by the polariscope, it presents a striped or fringed appear-

Fig. 79.

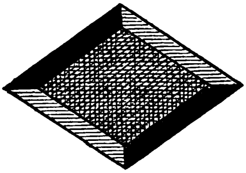


Section of the Pyramid and Part of the Prism of Amethyst.

ance, variegated with the most gorgeous and brilliant tints. This is owing to its being composed of alternate minute strata of right and left-handed quartz, whose planes of polarization are parallel to the principal axis of the prism.

Topaz sometimes presents a remarkably composite structure. It belongs to the right rhombic system, and presents, when regularly formed, two systems of rings. Cut at right angles to the axis it often presents a central rhomb, "surrounded by a border in which the optic meridians of the alternate sides are inclined at a quarter of a right angle to that of the central compartment, and half of a right angle to each other. In consequence, when such a rhombic plate is held with its long diagonal in the plane of primitive polarization, two opposite sides of the border appear bright, the other two black, and the central compart-

Fig. 80.

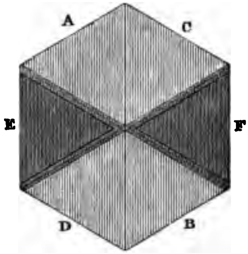


Topaz.

ment of intermediate brightness. Such specimens often present the phenomena of dichroism in the central compartment, while the border is colourless in all positions."*

Sulphate of potash is composed of six crystals belonging to the right prismatic system, joined so as to form a single or double six-sided pyramid, and simulating the crystals of the rhombohedric system. When, therefore, we put a slice of it, cut at right angles, to the axis of the pyramid, in the polariscope, we observe not a circular cross of rings, but a tesselated structure.

Fig. 81.



Sulphate of Potash.

One variety of *apophyllite*, called *tessellite*, presents a remarkable structure of the same kind; but its phenomena are still more extraordinary. Apophyllite is composed principally of silicate of lime, with a little silicate of potash. It crystallizes in right square prisms. Plates cut transversely to the axis, and examined by polarized light, appear to consist of nine crystals contained within a number of parallel veins or plates. The central crystal has only one axis of no double refraction, the others two. (See p. 199.).

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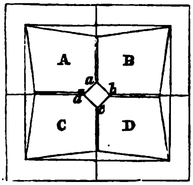
* Herschel, *Encyc. Metrop.*

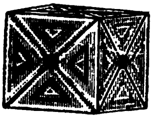
Fig. 82.



Tesselite or Tesselated Apophyllite.

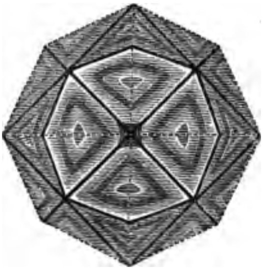
Analcime or *Cubizite* is another remarkable crystal. It consists principally of silicate of alumina with silicate of soda. It crystallizes in the form of the cube, or some form allied to this, as the icosatetrahedron. Instead of being without double refraction, as cubical crystals usually are, it presents a number of planes of no double refraction. It is, therefore, a com-

Fig. 83.



Analcime.

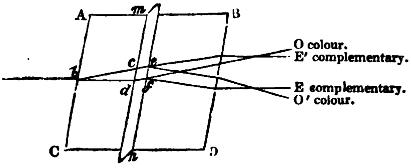
Fig. 84.



pound crystal, that is, is composed of a number of crystalline parts disposed symmetrically. (See p. 194.)

And here also may be noticed what has been called *interrupted Iceland spar.* Some specimens of Iceland spar give four or even more images, which sometimes exhibit complementary tints. They owe this property to the presence of one or more intersecting or interrupting films or strata of the same substance, placed perpendicularly to the short diagonal of the faces of the crystal. This film acts like the depolarizing plate in the polariscope, while the two portions of the crystal between which it is placed, act, the one as the polarizer, the other as the analyzer of the polariscope. Crystals like these, which thus exhibit their colours and rings *per se*, that is, without the polariscope, have been called by Sir John Herschel *idiocyclophanous* (from ἴδιος *proper*, κύκλος *a circle*, and φαίνω *I appear*). Similar phenomena are sometimes exhibited by crystals of

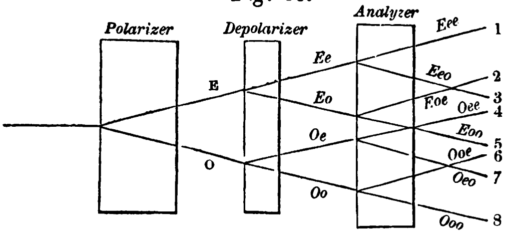
Fig. 85.



Idiocyclophanous Crystal of Calc Spar.

nitre, and still more frequently by *bicarbonate of potash.* Suppose the crystal to be made up of three pieces, or *polarizer*, *depolarizer*,

Fig. 86.



and *analyzer*, the modifications of the ray may be represented by this diagram. These interfere in two, and produce four figures; two of one colour, and the other two of one colour, but complementary to the first two.

COLOURED POLARIZATION IN ELLIPTIC AND CIRCULARLY POLARIZED LIGHT.

Thus far we have spoken only of the colours developed in crystals by *plane* polarized light. It will be necessary now to advert to the corresponding phenomena when the light is circularly or elliptically polarized, in which case the systems of rings undergo some remarkable modifications.

If a ray of circularly polarized light be transmitted through a thin film of a doubly refracting crystal, and the emergent light be analyzed by a doubly refracting prism, two rays of complementary colours are produced.

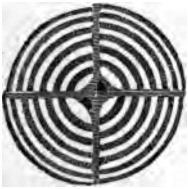
In this character, circularly polarized light is decidedly different to common or unpolarized light, which when submitted to the same examination presents no colour. Rectilinearly polarized light, however, agrees with the circular light in producing complementary tints; but they are not the same in the two cases; those produced by circular light differing from those of rectilinear light by an exact quarter of a tint, either in excess or defect, as the case may be.

To illustrate these facts, place a film of selenite, of uniform thickness, in the polariscope, and observe the tint which it yields by rectilinearly polarized light. Then interpose, between the polarizing plate and the selenite film, a circularly polarizing apparatus (as Airy's mica plate, or Fresnel's rhomb), and the tint seen by the analyzer immediately changes.

If a plate of calcareous spar, cut to show the circular rings and cross by rectilinearly polarized light, be placed in the polariscope, and circularly polarized light be used, we observe a system of rings and a cross (*fig.* 87.), but which are very different to those seen by rectilinearly polarized light.

The rings are divided into quadrants by the cross, every other quadrant being similar, while the adjacent ones are dissimilar. The rings appear to be abruptly and absolutely dislocated, those in the two alternate quadrants being pushed outwards or from the centre, by ¼ of an order, and those of the intermediate quadrants being as it were pulled inwards by ¼ of an order. Instead of a black cross, we have a luminous one, the intensity of its light being uniform, and about equal to the mean intensity. If the plane of incidence pass through 135° and 315°, the phenomena of adjacent quadrants are exactly interchanged. But the most important difference produced by circularly polarized light, is, that no alteration is made by turning the analyzing plate round the incident ray.

Fig. 87.



Rings and Cross of Calc Spar produced by circularly polarized light.

If a plate of a biaxial crystal, as of nitre, be examined by circularly polarized light, we observe the double system of rings, but the black cross disappears. Every alternate semicircle of rings presents the appearance of dislocation.

The origin of the tints produced by circularly polarized light have been so clearly and concisely explained by Sir John Herschel, that I cannot do better than use his words:

"When," says this eminent philosopher, "a ray propagated by circular vibrations is incident on a crystallized lamina, it may be regarded as composed of two; one polarized in the plane of the principal section, the other at right angles to it, of equal intensity, and differing in phase by a quarter undulation. Each of these will be transmitted unaltered; and, therefore, at their emergence, and subsequent analysis, will comport themselves, in respect of their interferences, just as would do the two portions of a ray primitively polarized in azimuth 45°, and divided into two by the double refraction of the lamina; provided that a quarter undulation be added to the phase of one of these latter rays. Now, such rays will produce, by the interference of their doubly refracted positions, the ordinary and extraordinary tints due to the interval of retardation within the crystallized lamina. Hence, in the present case, the tints produced will be those due to that interval, *plus* or *minus* the quarter of an undulation added to, or substracted from, the phase of one of the portions; and, consequently, will differ one-fourth of a tint in order from that which would arise from the use of a beam of ordinary polarized light, incident in azimuth 45° in the lamina."

In certain media circularly-polarized light gives rise to very peculiar effects. If a ray of circularly-polarized light be transmitted through a column of *syrup* or *oil of turpentine, lemon,* &c., and then analysed, either by a Nichol's prism, or a doubly-refracting prism, no colour is produced; for the circular wave is propagated along the liquid without suffering subdivision, and, therefore, at its emergence no colour can be produced by the analyzer.

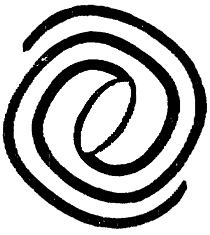
In this character circularly-polarized light agrees with common or unpolarized light, but differs from plane polarized light.

"Circularly-polarized light," says Fresnel, "differs from polarized light in not sensibly developing colours in plates of *quartz* perpendicular to the axis." According to the wave hypothesis this ought to be the case; for "a ray propagated by circular vibrations, when incident on rock crystal in the direction of the axis, will (by hypothesis) be propagated along it by that elasticity which is due to the direction of its rotation, the wave then will enter the crystal without further subdivision, and there will be no difference of paths or interfering rays at its emergence; and, of course, no colours produced on analyzing by double refraction."

I confess, however, I have not been able precisely to verify this statement, though, I doubt not, my failure has arisen from some defect in the apparatus used to produce circular polarization. I have always found a very feeble tint of colour in the axis. As Mr. Airy has very accurately described the phenomena which I myself have repeatedly seen, I prefer quoting his words*:

"If circularly-polarized light pass through the quartz, on applying the analyzing plate, instead of rings, there are seen two spirals mutually enwrapping each other (as in *fig.* 88.). If the [Fresnel's] rhomb be placed in position 135°, the figure is turned through a quadrant. If the quartz be left handed†, the spirals are turned in the opposite direction. The central tint appears to be white. With the rhomb which I have commonly used (which is of plate glass, but with the angles given by Fresnel for crown-glass), there is at the centre an extremely dilute tint of pink: I think it likely that this arises from the error in the angles, as the intensity of the colour bears no proportion to that in other parts of the spiral."

Fig. 88.



Spirals of Quartz, produced by circularly-polarized light.

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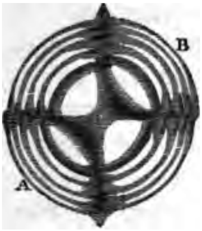
* *Cambridge Transactions*, 1831. p. 8.

† This distinction will be fully explained in a subsequent Lecture.

If a plate of right-handed quartz be superposed on a plate of left-handed quartz of equal thickness, and examined by circularly-polarized light, the left-handed slice being nearer to the polarizing plate, we observe by means of the analyzer four spirals (proceeding from a black cross in the centre), which cut a series of circles at every quadrant. At some distance from the centre the black brushes are seen. If the right-handed slice be nearer the polarizing plate, the spirals are turned in the opposite directions.

[The coloured rings in calc spar produced in elliptically polarized light present some singular modifications of form. When the ellipticity approaches near to being circular, their general form approaches that represented before (in *fig.* 87.); when the ellipticity is more eccentric, the rings assume a more peculiar but still dislocated appearance; which is in general represented in the figure (89.).

Fig. 89.



These modifications are all represented by the forms assumed by the analytical expressions derived from the undulatory theory; both for circularly * and elliptically † polarized light.

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* Airy's Tract, art. 160.

† Airy's paper on Quartz, &c. *Camb. Trans.*, 1831. *See* also *Phil. Trans.*, 1843. pt. i. p. 42.

One peculiar appearance presented when the analyzer is at half right-angles to the plane of incidence, is that of a *distortion* of the figures of the quadrants, as well as *dislocation.* This was first deduced from the same formulas by Prof. Powell.*

In the same paper there is described and figured the most convenient form of apparatus for experiments in elliptic polarization by reflexion from metals, &c.

In all elementary works it has been usual to draw the distinction that plane polarized light reflected from *metallic* surfaces, and from *these only*, becomes elliptically polarized.

The experiments of Sir D. Brewster require this to be extended to the case of *metallic ores.* It has also been extended to *films* of oxide, &c., on the surfaces of metals, in which (as in Nobili's films, &c.) the degree of ellipticity goes through some singular changes, which are detailed in the paper by Prof. Powell before referred to.†

In that paper (p. 38.), it was also announced (as is believed for the first time), that elliptic polarization was procured by reflection from a surface not decidedly metallic; or, at least, containing the most minute proportion of metal, viz., *Plumbago;* and still more remarkably in a substance containing no metal whatever, viz., *Indian ink;* both, however, consisting of *carbon.**

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* *Phil. Trans.* 1845, pt. ii. p. 272.

† *Phil. Trans.* 1843, pt. i.

This idea was followed out to a much more remarkable extent in the experiments of Mr. J. A. Dale, M. A., of Balliol College, Oxford, to which due justice has not been done, and of which there exists no better account than a brief abstract in the Proceedings of the British Association.†

Mr. Dale has there shown, that chromate of lead, litharge, indigo, realgar, diamond, sulphuret of zinc, glass of antimony, sulphur, tungstate of lime, carbonate of lead, hyacinth, arsenious acid, as well as a few other minerals in a less degree, all possess the property of giving *elliptically polarized light by reflexion;* and he has connected these facts with the condition that all these are substances of *very high refractive power,* and has thus connected them directly with the case of *metals,* in which that power is extremely high: or has established the general and important law, that *elliptic polarization by reflexion is in all cases occasioned simply by the high refractive power of the substance, and in some determinate ratio to its amount.*]

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* Brit. Assoc. 1846, Sec. Proc. p. 4.

† Report, 1846, Sec. Proc. p. 5.

LECTURE IV.

ON ROTATORY POLARIZATION.

THIS curious branch of the subject originated in the observation of a peculiar modification which polarized light undergoes in passing through quartz (some of whose peculiar properties have been already referred to), first made by M. Arago, the distinctive characters and properties of which it will now be our object to explain.

[It should first be observed that this property has been sometimes called "circular polarization;" but there is some confusion involved in this designation, the same term having been used in a different sense, as we have before explained. The term "rotatory" polarization has been used by others, and is clearly preferable, as, while it avoids the ambiguity, it in fact more clearly describes the phenomenon.

In the present instance the property of *rotatory polarization* may be best conceived in theory by supposing a ray *plane* polarized, but in which, at successive distances along its direction, the *plane of polarization* deviates from its original direction and is *twisted* round in the form of a screw or helix. Here the entire form of the *ray* in *sensible* lengths *resembles* that of the *wave* in *infinitesimal* distances in *circularly*-polarized light; but the whole case is essentially distinct, and must be carefully kept so in the apprehension of the student. The directions of the successive planes of polarization may be familiarly represented by the *edges* of the steps in a corkscrew staircase. Here the *vibrations* are *plane*, but the plane of the wave becomes a *twisted* surface; in circular polarization the *vibrations* themselves are *circular*, and there is *no plane* of polarization.]

Among the varieties of quartz there are found to be two classes in which this property is differently characterised, distinguished by its manifesting itself in opposite directions, and called dextro-gyrate, or right-handed, and lævo-gyrate or left-handed. Unfortunately, writers are not agreed in the application of these terms, whence much ambiguity has arisen: what Biot terms left-handed is named by Herschel right-handed rotation, and *vice versâ*. There is, however, no difference in the facts, but only in the designation. If, on turning the analyser from left to right, the colours *descend* in the order of Newton's scale — that is, succeed each other in the order of the colours of their plates, reckoning from the central black as the highest point — Biot designates the polarization as right-handed, or +, or ↗; whereas, if they descend in the scale by turning the analyser *from right to left*, he terms it *left-handed*, or –, or ↤.

Sir J. Herschel, on the other hand, supposes the observer to look in the direction of the ray's motion. "Let the reader," he observes, "take a common corkscrew, and, holding it *with the head towards him*, let him use it in the usual manner as if to penetrate a cork. The head will then turn the same way with the plane of polarization as a ray in its progress *from* the spectator through a right-handed crystal may be conceived to do. If the thread of the corkscrew were reversed, or what is termed a *left-handed* thread, then the motion of the head, as the instrument advanced, would represent that of the plane of polarization in a left-handed specimen of rock crystal."

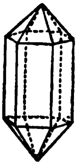
I shall adopt Biot's nomenclature, and designate the polarization right-handed or left-handed, according as we have to turn the analyzing prism to the right or to the left to obtain the colours in the descending order.

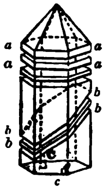
The term quartz, the etymological origin of which is not clearly made out, is applied to some of the crystalline forms of silica. The transparent variety, called *rock* or *mountain crystal*, is the kind used for optical purposes.

Very perfect transparent crystals are found near Bristol and in Cornwall, and are called *Bristol* or *Cornish diamonds.* The opticians cut some of the most limpid and large crystals, which usually come from the Brazils, for making lenses for spectacles and eye-glasses, and which they denominate *pebbles.*

Figs. 90 and 91.

Ordinary Crystals of Quartz.





Different Modes of slitting Quartz for Optical Purposes :

a a, Plates transverse to the prismatic axis, for showing (in the polariscope) the system of circular rings (*fig.* 92.).

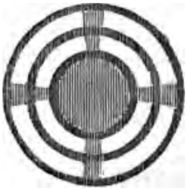
b b, Plates cut obliquely to the axis, for showing the straight bands.

c c, Wedges for making Wollaston's quartz doubly refracting prisms.

Quartz belongs to the rhombohedric system. Its most common form is the six-sided prism, terminated by six-sided pyramids (*fig.* 90.). Its fracture is conchoidal.

Now, as quartz belongs to the same system of crystals to which Iceland spar belongs, it might be expected that when we place a plate of it, cut perpendicularly to its principal or prismatic axis (*fig.* 91. *a, a*), in the polariscope, we should observe the cross and a system of circular rings, as in the case of Iceland spar and other crystals of the rhombohedric system. But this is not the case. We do, indeed, observe a system of rings, but the centre of the cross is wanting (*fig.* 92.). Instead of the cross within the inner ring we observe a uniform tint, the colour of which changes when the analyzer is revolved; and, in succession, a series of colours is brought into view. But the order of succession (supposing the direction or revolution of the analyzer to remain the same) varies in different crystals. Thus, suppose we turn the analyzer right-handed, that is, as we screw up, the colours succeed each other, with a certain thickness of the crystal, in this order, — *red, orange, yellow, green, purple, red* again, and so on, in the ascending order of Newton's scale, on the colours of thin plates, before given.* In other specimens this order will be reversed. So that, to obtain the same order of succession, the analyzer must be turned in the one case right-handed, or as we screw up, in the other left-handed, or as we unscrew. This will be

Fig. 92.



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* See p. 41.

rendered more obvious by the following diagrams:

Fig. 93.

Right-handed.

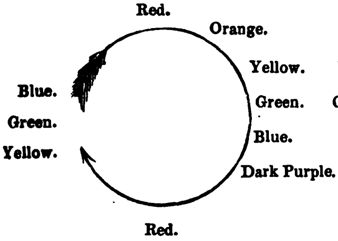
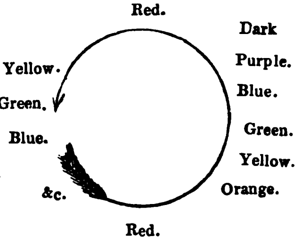


Fig. 94.

Left-handed.

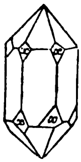


In each of these diagrams the arrow shows the direction in which the analyzer is to be rotated, in order to obtain the spectral tints in the ascending order of tints, which in this intance belong to the third order of Newton's scale.

Hence those specimens of quartz which present the colours in the descending order by a right-handed rotation of the analyzer, are denominated *dextrogyrate*, or *right-handed quartz;* while those which present them by a left-handed rotation are called *lævogyrate*, or *left-handed quartz*.

Between these two varieties there has been discovered by Sir John Herschel another difference. In that form of quartz termed by Haüy *plagiedral* (from *πλάγιος oblique*, and

Fig. 95.



Plagiedral Quartz.

ἕδρα a base), it has been found that when the unsymmetrical or plagiedral faces (*fig.* 95. *x*) lean to the right, the polarization is right-handed, and, *vice versâ*, when they lean to the left the polarization is left-handed. So that the cause, whatever it may be, which determines the optical phenomena, is also connected with the production of the plagiedral faces.

If, instead of using white light in our experiment, we employ homogenous light, we find the plane of polarization of the incident rays is turned or made to rotate either to the right or left, according as the quartz plate is either right-handed or left-handed. This rotation of the plane of polarization of the incident ray is proportional to the thickness of the plate. The colours produced by thin plates are broader and less numerous than those produced by thick plates. If two plates be superposed, the effect is very nearly the same as that produced by a single plate whose thickness is either the *sum* or the *difference* of the thicknesses of the two plates, according as they are of the same kind (that is, both either right-handed or left-handed), or of opposite kinds (that is, one right-handed, the other left-handed). Thus, if the rotation of the red rays, effected by a plate of quartz of $\frac{1}{25}$th of an inch thick be equal to $17\frac{1}{2}°$, that produced by two superposed plates of equal thickness, taken from the same crystal, will be $2 \times 17\frac{1}{2}° = 35°$. On the other hand, if we combine a plate of right-handed quartz of $\frac{1}{25}$th of an inch thick with a plate of left-handed quartz of $\frac{4}{25}$ths of an inch thick, the same effects are produced as if we had employed a left-handed plate of $\frac{3}{25}$ths of an inch thick. When the thicknesses of the two dissimilar plates are equal, "the plates, of course, destroy each other's effects, and the system of rings with the black cross will be distinctly seen." (*Brewster.*)

The rotation of the plane of polarization increases with the refrangibility of the rays. Thus it is greater with violet than with blue, with blue than yellow, and with yellow than red.

Homogeneous Ray.	*Arc of Rotation.*
Extreme Red	17° 29′ 47″
Limit of Red and Orange	20° 28′ 47″
" Orange and Yellow	22° 18′ 49″
" Yellow and Green	25° 40′ 31″
" Green and Blue	30° 2′ 45″
" Blue and Indigo	34° 34′ 18″
" Indigo and Violet	37° 51′ 58″
" Extreme Violet	44° 4′ 58″

I come now to the explanation which the wave hypothesis offers of these phenomena.

When the light, rectilinearly polarized by the first tourmaline plate, is incident on the quartz plate, it suffers double refraction. To prove this, Fresnel contrived a combination of a right-handed prism, and two halves of a left-handed one, by which he doubled the separation of the two rays, and in this way managed to demonstrate the actual existence of double refraction in the principal or prismatic axis of quartz. This is a most remarkable fact. In the principal or prismatic axis of every other known crystal of the rhombohedric system, double refraction does not exist.

But the two rays thus obtained differ in their properties from those produced by Iceland spar and other doubly refracting crystals; for while the latter are rectilinearly polarized, those of quartz are circularly polarized. Now every circularly-polarized ray is equal to two rectilinearly polarized waves, differing in their progress an odd number of $\frac{1}{4}$ undulations. It follows, therefore, that the two circularly polarized waves are equal to four rectilinearly polarized waves. Hence, then, to explain the phenomena, we must assume that the rectilinearly polarized ray (which I shall call R) incident on the quartz, is resolved into two others (A and B) of equal intensity, the one (A) polarized in a plane 45° inclined to the *right*, the other (B) 45° inclined to the *left* of the plane of polarization of the primitive ray (R). Let us further conceive that each of the two rays (A and B) is resolved into two other rays, namely, A into A*a* and A*b*, and B into B*a* and B*b*. A*a* and A*b* are polarized in one plane, viz., + 45°, while B*a* and B*b* are polarized in another plane, viz.,—45°. A*a* and B*a* have each their phases advanced, or + $\frac{1}{8}$ undulation, while A*b* and B*b* have each their phases retarded, or —$\frac{1}{8}$ undulation.* Now, if we suppose these four rays to be combined two and two in a cross order, we shall have resulting two circularly polarized rays, one right-handed, the other left-handed. Thus A*a* and B*b* combine to form a left-handed ray, while A*b* and B*a* form a right-handed one; for when the advanced system of waves has its plane of polarization to the right of that of the retarded system, the ethereal molecules rotate from right to left; whereas they rotate from left to right when the first plane is to the left of the second.

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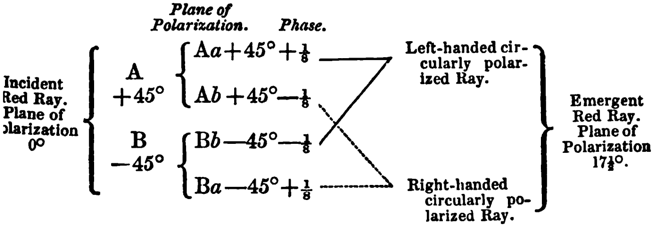
* "It results from the laws of interference," says Fresnel, "that a system of waves, polarized rectilinearly, may be replaced by two others, polarized at right angles to each other, and coinciding in their route; and that for each of these we may substitute two other systems of waves having the same plane of polarization, but the one advanced, the other retarded $\frac{1}{8}$th of an undulation; and thus separated $\frac{1}{4}$th of an undulation. In this way are obtained four systems of waves of equal intensity, of which two, polarized at right angles to each other, are $\frac{1}{4}$th of an undulation behind the two others polarized in the same planes."

These two circularly polarized rays are propagated along the axis of quartz with unequal velocities. In right-handed quartz the right-handed ray is transmitted with greater velocity, in left-handed quartz with lesser velocity than the left-handed ray; and thus at their emergence one is in advance of the other. If the surface of egress or ingress be *oblique* to the axis, the two circularly polarized rays will emerge in different directions; but if it be *perpendicular* (as in the experiment under examination) they will emerge superposed, and will compound a single ray polarized in a single plane. Now this plane is removed from the plane of primitive polarization by an angle proportional to the interval of retardation (therefore, proportional to the thickness of the crystal) and to the refrangibility of the ray.

Thus, then, the differently coloured rays emerge from the quartz plate polarized in different planes; hence, by rotating the analyzer, they are successively transmitted and brought into view.

The following diagram may, perhaps, serve to render more intelligible the explanations of the action of a plate of quartz, of one millimètre (0·03937 of an English inch) in thickness, on the incident rectilinearly polarized red light.


Plane of Polarization.
Phase.
Incident Red Ray. Plane of larization 0°
A +45°
B −45°
Aa +45° +⅛
Ab +45° −⅛
Bb −45° −⅛
Ba −45° +⅛
Left-handed circularly polarized Ray.
Right-handed circularly polarized Ray.
Emergent Red Ray. Plane of Polarization 17½°.

A succession of quartz prisms does not give a further multiplication of images — a circumstance which distinguishes the double refraction of quartz from that of Iceland spar and other crystals.

The above explanation is applicable only when the direction of the rays *coincides* with the principal axis of the crystal. When it is *inclined* to this axis, Mr. Airy has shown that the two resulting rays are *elliptically polarized*, the elliptical vibrations in the two rays being in opposite directions (that is, one right-handed, the other left-handed), and the greater axis of the ellipse is for the extraordinary ray in the principal plane of the crystal, and for the ordinary ray in a plane perpendicular to the principal one. The ratio of the axes in these ellipses varies with the inclination of the ray to the principal axis of the crystal. When the direction of the ray coincides with this axis, the ratio is one of equality, and the ellipses become circles. But when the ray is inclined to the axis, the ratio increases indefinitely with the inclination. "It is also necessary to suppose that the axis of revolution of the spheroid (prolate for quartz), in which the extraordinary ray is supposed to diverge, is less than the radius of the sphere into which the ordinary wave diverges."

Hitherto we have had no satisfactory theory of the cause of the unequal velocities with which the two rays are transmitted along the principal axis of quartz. We conceive that it must depend either on some peculiarity in the molecules themselves, or in their mode of arrangement. "The crystal," says Fresnel, "cannot be constituted from right to left as it is from left to right, either in virtue of the arrangement of its particles, or of their individual constitution." If it be a molecular property, it must be acquired in the act of crystallization, by the mutual action of the molecules on each other, for other forms of silica, as well as melted quartz, are devoid of it. An helicoidal arrangement (right or left-handed, as the case may be) of the molecules furnishes a physical explanation of the fact above referred to. It has been objected to this hypothesis, that it is not applicable to the case of rotatory polarizing liquids. But as the rotatory polarization of quartz is dependent on direction, while that of liquids is independent of it, it is tolerably clear that the cause must be different in the two cases. In the first, it may depend on the arrangement of the molecules; in the second, on some peculiarityin the molecules themselves.

If two plates of quartz, cut obliquely to the principal axis of the crystal (*fig.* 91. *b b*, *b b*), be superposed crosswise and examined in the polariscope, they present a series of parallel coloured bands or stripes, with a central black or white stripe. When the tourmaline plates are crossed, the central stripe is black; when they coincide, it is white. The lateral coloured stripes seen in the one case are complementary to those seen in the other.

Amethyst is a mixture of right and left-handed quartz, and will be hereafter noticed among tesselated crystals.

*Rotatory Polarization by Fluids.**—Some

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* For the discovery of the rotatory polarizing of fluids *see* Biot, *Ann. Chim. Phys.* 74. 429, 430.; also Biot, *Phys. Exp.*, t. iv. 542.

One part tartaric acid One part water	Formed a solution which in a tube of 500 millimètres long had a rotation of 22°. (Burckhardt and Guibert).

liquids possess this remarkable property. The following are the most important:—

Volatile oils (those of mustard and bitter almonds excepted).

Naphtha.

Aqueous solutions of several kinds of *sugar*, *dextrine*, *tartaric acid*, and *tartrates* (tartrate of alumina excepted).

Diabetic urine.

Albuminous urine.

Alcoholic solutions of *camphor* and *artificial camphor.*

Most *vegetable juices.*

Biot found that vaporization did not destroy the rotatory polarization of oil of turpentine.

The following liquids have been found devoid of this property:—

Water.

Alcohol.

Pyroxilic spirit.

Pyroacetic spirit.

Olive oil.

Volatile oil of mustard.

„ „ *bitter almonds.*

Claret (perhaps a trace of ↘).

Champagne.

Citric acid (dissolved in water).

Mannite (ditto).

Liquorice sugar (dissolved in water).

Glycerin.

The apparatus necessary for observing this property of fluids consists essentially of three parts; viz., a polarizer, a tube to contain the fluid, and an analyzer.

The *polarizer* is an unsilvered glass mirror, a bundle of parallel glass plates, or a Nichol's prism. Biot uses the first, while Ventzke employs the last. A plate of glass, blackened at the posterior surface, answers very well. Sometimes a second mirror (of silvered glass) is used to throw the light on the polarizing plate.

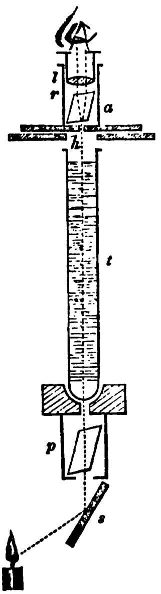
The *tube*, to hold the liquid, should be from six to twenty-four inches long. It is to be filled with the fluid under examination, and to be closed at each end by a flat glass plate. In Biot's very accurate and elaborate apparatus, he also has two or three perforated diaphragms of sheet silver or platinum, placed at intervals in the tube, to exclude the light reflected from the sides of the tube, but to admit those rays which traverse the axis of the tube.

The *analyzer* should be either an achromatic, doubly refracting prism, or a Nichol's prism. Biot uses a doubly refracting prism of calc spar, made of a rhombohedron of this substance, rendered achromatic by replacing a portion of the crystal by a glass prism. Achromatic quartz prisms are objectionable, since they are never so accurately prepared as to yield two images only, but always four; of which two, however, are very faint. Ventzke uses a Nichol's prism as the analyzer.

[The apparatus of M. Biot is of the most complete and expensive description, and is probably indispensable for the performance of very accurate experiments and delicate researches. But for the more ordinary purposes of the student, Prof. Powell devised a far simpler form of the apparatus, which can be readily constructed. It consists essentially of the following parts: —

A small silvered mirror (*s*) throws the light up through a Nichol prism (*p*) as the polarizer, whence it passes through a hole in a frame, on which rests the bottom of an ordinary test tube (*t*) placed vertically and filled with the liquid under examination. The emergent light can give no distinct image (which is obtained and is essential in Biot's method), but it passes through a small hole (*h*) in the upper part of the frame, on which rests a tube (capable of turning about its axis and furnished with a graduated rim for measuring the rotation), and containing the analyzer (*a*), a rhomb of Iceland spar in its natural state (*r*), of sufficient thickness to give two images of the hole (*h*) without overlapping: these images are then magnified by an eyelens (*l*), and thus their changes of colour are made sufficiently conspicuous, however irregularly the light may be refracted in the tube, provided it be bright enough.

Fig. 96.



The frame, &c., must be made so as to allow of raising or lowering the analyzer according to the length of tube employed: the tube should also be enclosed in an opaque case, to keep out extraneous light.

It is also very convenient (if not necessary) to be able to compare two different tubes without disturbing the rest of the arrangement. Hence, the part of the frame carrying the tube is so contrived as to carry two tubes side by side and to turn on a pivot, so that either can be brought under the analyzer in immediate succession.

For a full description the reader is referred to a paper in the *Phil. Mag.* April, 1843.]

The amount of rotation which a ray of light suffers during its passage through the liquid is measured by an index attached to the analyzer, and moving on a graduated circular metallic plate. Before the tube containing the liquid is introduced, we must fix the zero, or 0°. If a doubly refracting prism be the analyzer, the index is made to point to zero, when the ordinary image alone is seen. If, however, a Nichol's prism be used as analyzer, the index is arranged to point to 0° when the light is excluded; or, in other words, when the light, transmitted by the polarizer, is extingushed by the analyzer.

Homogeneous light is generally employed when we wish to measure the arc of rotation affected by a liquid on a luminous ray. Red light is usually selected, because this is the only homogeneous light which can be isolated by coloured glass. We, therefore, place a plate of red glass between the eye and the analyzer.

If, when the index points to zero the tube containing a rotatory polarizing liquid be introduced, the second or extraordinary image immediately becomes evident, if the doubly refracting prism be used as analyzer. By turning the latter round to the right or to the left, as the case may be, this second image disappears (when homogeneous light is used), and the arc traversed by the index from the zero measures the angle of deviation of the ray.

If, however, a Nichol's prism be employed, it no longer excludes the light when the index stands at zero, but requires to be rotated a certain number of degrees to do so, and the arc of rotation is here a measure of the rotative power of the liquid.

The explanation of the action of these liquids on the incident rectilinearly polarized light is similar to that already given for the axis of quartz; with the exception, that in the case of quartz, the circular double refraction may depend on the arrangement of the molecules, whereas in liquids it must arise from some property of the molecules themselves.

The rotatory polarization of liquids is a *molecular property:* it depends on their individual constitution, without any relation to the position of the particles themselves, or to their mutual distances, or to their state of repose or motion (Biot, *Mém. de l'Acad.* xiii. p. 46.).

I proceed now to examine some of the liquids which possess the property of rotatory polarization.

First, with regard to the *essential* or *volatile oils.* Most of these bodies are rotatory polarizers: indeed, I know but two exceptions to this statement, viz., oil of mustard and oil of bitter almonds. Some turn the planes of polarization to the right, others to the left, but the intensity of their rotative power varies considerably, as the following table shows:—

CIRCULAR POLARIZATION OF THE VOLATILE OILS.

1. *Left-handed*, or *Lævogyrate*.

	Arc of Rotation of the Red Rays through a thickness of 200 Millimètres calculated.
Oil of Turpentine (152 millimètres—45°)	59° 21′
" Mint	32° 28′
" Anise	1° 52′
" Rue	?
Naphtha (tube 163 millimètres—12° 40′)	15° 21′

2. *Right-handed*, or *Dextrogyrate*.

Oil of Lemon	110° 53′
" Bergamot	38° 16′
" Bigarade	157° 89′
" Citron	—
" Limette	—
" Neroli	—
" Fennel	26° 32′
" Caraway	131° 58′
" Lavender	4° 04′
" Rosemary	6° 58′
" Knotted Marjoram	23° 68′
" Sassafras	7° 06′
" Savine	14° 12′

This table is a very instructive one. It shows that isomerism has no connection with rotatory polarization, for of three isomeric oils (turpentine, lemon, and bergamot) mentioned in this table, one is lævogyrate, the others dextrogyrate. We see also, that oils derived from plants of the same natural family (as the oils of anise, fennel, and caraway, from the *umbelliferæ*, and those of mint, lavender, and rosemary, from the *labiatæ*) differ in respect of their rotatory polarization. In some cases, perhaps, this fact might be available to the pharmaceutical chemist in detecting mixtures of one oil with another, as the adulteration of oil of peppermint with oil of rosemary, recently mentioned by Mr. Herring. (See *Pharmaceutical Journal*, vol. i. p. 263..)

Some kinds of *sugar*, when dissolved in water, yield solutions which have in a greater or less degree the property of rotating the planes of polarization, some to the right, others to the left. Hence, polarized light may be sometimes used as a test of the presence of sugar, and the degree of rotation becomes an indication of the quantity and even quality of the sugar present. Biot examined by this test a specimen of sugar-cane juice, and found that it indicated the presence of 20 or 21 per cent. of sugar. Peligot subsequently analyzed it, and found 20·9 per cent. of sugar. Biot, therefore, suggests that those who make, as well as those who refine sugar, might resort to this test as a means of determining the amount of sugar in different juices or solutions. To the colonist it would prove useful by pointing out the saccharine strength of the juice at the mill, and to the sugar refiner it would be valuable by enabling him to determine the absolute strength of raw sugar.

The sugars are prepared for examination by dissolving them in water, and decolorizing the solutions when necessary, by filtering them through purified granulated animal charcoal.

Several sweet or saccharine substances do not indicate any rotatory polarization, and of those that do, some indicate right-handed, others, left-handed polarization.

1. Cane sugar		*Right-handed.*
2. Grape sugar (*Glucose* of Dumas)		*ditto.*
3. Incrystallizable sugar(*Chulariose* of Soubeiran)	*a.* Incrystallizable sugar of honey	*Left-handed.*
	b. Incrystallizable sugar, obtained by the action of acids on cane sugar	*ditto.*
	c. Incrystallizable sugar of the juices of fruits	*ditto.*
	d. Incrystallizable sugar obtained by the alteration of cane sugar. This constitutes the greater part of molasses.	*ditto.*
4. Mannite		O
5. Glycerin		O
6. Liquorice sugar		O

The grape sugar referred to in this table exists ready formed in honey, and in diabetic urine. It is deposited when the acidulous juices of fruits have been saturated and sufficiently concentrated. Moreover, it is produced by the action of diastase on starch, as well as when syrup, obtained by the action of weak acids on starch or sugar, is abandoned to itself.

The following table, taken from a memoir by Biot, shows the extent of rotatory power possessed by different sugars :—

ROTATION OBSERVED WITH RED GLASS THROUGH A SOLUTION OF 152 MILLIMÈTRES IN LENGTH.

	Proportion of Sugar in one of the Solutions.	*Arc of Rotation.*	
Sugar candy 1. Aqueous solution	0·25 ...	23° 28′ 45″	↗
" 2. "	0·50 ...	51° 21′ 45″	↗
" 3. "	0·65 ...	70° 11′ 15″	↗
Cane sugar syrup, boiled, and rapidly cooled..................	0·244 ...	16° 50′ 33″	↗
Sugar of milk, crystallized (aqueous solution)	0·14 ...	10° 21′ 40″	↗
Starch sugar, white grains (ditto)	0·648 ...	48° 30′ 0″	↗
Grape sugar syrup	— ...	— — —	↘
" in white grains (aqueous solution)	0·1558 ...	— — —	↗
Crystallizable principle of honey	0·34201...	16° 47′ 30″	↗
Uncrystallizable ditto	— ...	— — —	↘

Cane sugar, dissolved in water, causes *right-*handed polarization. A strong syrup made with refined sugar shows the colours most brilliantly. When this kind of sugar is subjected to heat, especially in contact with acids, it loses its crystallizability, and then acquires *left*-handed polarization. In the manufacture of barley-sugar, hardbake, &c., the makers of these kinds of hard confectionary use a little cream of tartar to destroy the crystallizability of sugar. Soubeiran found that a syrup of cane-sugar heated by a salt-water bath, the air being excluded, underwent a series of remarkable changes in respect of its rotative power.

		Arc of Rotation for mean Yellow Ray for a length of 100 Millimètres.	
Syrup, primitive		+71	↗
"	After twenty hours	0	
"	After twenty-five hours	—11	↖
"	After sixty-four hours	0	
"	After seventy-two hours	+ 5	↗

Here, then, it appears, that cane-sugar ↗ gradually lost its rotative power 0°, and then became ↖. In this latter state it was probably uncrystallizable sugar. But this in its turn lost its rotative power 0°, and became ↗. The precise nature of the latter kind of sugar is not known.

In sugar-refining the object is never to let the syrup get beyond the first zero; that is, not to convert crystallizable into uncrystallizable sugar. Raw sugar contains, however, both crystallizable and uncrystallizable sugar. The latter alone should constitute treacle. But, from Soubeiran's optical examination, it appears that treacle contains a portion of crystallizable sugar.

The optical characters of sugar have been made use of to detect fraud in pharmacy. In 1842, more than a ton of a substance purporting to be *manna* was offered for sale in Paris at less than five pence per pound, the excuse given for the unusually low price was, that cash was immediately required. Suspicion was raised, and the substance was submitted to careful examination, the result of which was the establishment of the fact, that it was not manna, but potato-sugar. Its aspect, taste, fermentability (mannite not being fermentable), and the presence of sulphate of lime proved this. Biot submitted it to a very careful optical examination, and found its characters to be those of a starch-sugar. Manna contains two kinds of saccharine matter, one called *mannite*, and the other a *fermentable sugar*. Now, mannite, when pure, has no rotative power on polarized light, but commercial manna has a slight effect, owing to the presence of a small quantity of fermentable sugar. This fictitious substance, however, had the same effect, on plane polarized light, as sugar prepared by the action of acids on starch, when the action is arrested at the first phase of its transformation.

Vinous fermentation has been studied by the aid of polarized light. Take a solution of cane-sugar which has *right-handed* circular polarization. As soon as it begins to ferment it loses this property, but acquires *left-handed* polarization.

Polarized light has been proposed and used as a test of the presence of sugar in urine. To render diabetic urine available for this purpose, it must be decolorized by agitation with fresh prepared granulated animal charcoal, and subsequent filtration. The process is troublesome, tedious, and can only prove successful in the hands of persons familiar with the phenomena of polarized light. With all due deference to Biot, I do not think it will ever prove of much value in practical medicine. We have other, simpler, less laborious, and cheaper methods of detecting sugar in urine than the one now referred to. Moreover, it should be remembered, that albuminous urine possesses the property of circular polarization.

The substance called *dextrine* is starch-gum, and is soluble in water. It is usually prepared from potato-starch, either by torrefaction or by the action of a small quantity of nitric acid. A solution of it possesses the property of right-handed rotatory polarization, hence the name *dextrine,* applied to it by Payen and Persoz.

ADDITIONAL NOTES.

I.

Polarization of Starch.

Biot (*Comptes Rendus*, 1837, t. v. p. 905.) observes, that there is this physical difference between *amidine* and *dextrine*, — that *amidine*, in the state of fecula, is a body *actually* organized, while *dextrine* has lost all regular state of aggregation.

Fecula is an actually organized body. It produces, in polarized light, phenomena (seen by the microscope) which can only result from a body regularly constructed, and of which the interior constitution is established around the diameter, passing by the point of the surface where is found a sort of umbilicus, by which it is generally supposed that the feculaceous globule was attached to the walls of the cell when it was developed.

These phenomena are observed in all globules; but their effect on the polarized light is the more energetic as they are larger; this shows that it results from the successive action of all the layers of which they are formed.

When a globule has been broken or ruptured by some accident of trituration, the detached portions do not thereby lose their texture, for they continue to act on polarized light: as far as I am able to judge, they do it in the same manner as before they were separated from the whole.

Fecula, disaggregated by water and heat, or by weak acids and alkalis, does not present these phenomena. They have, then, only the molecular rotatory power, which is not sensible in so small thicknesses, and which is exercised according to other laws.

If, during the disorganization of the globule, we study the action of iodine upon it, we see the phenomena of coloration vary with the progress of the attenuation, and they cease when the globule has passed to the state of perfectly pure dextrine.

These observations, re-united to chemical isomerism, and to the constancy of the rotatory power in these successive states, may induce us to think that the organization or the disaggregation of the fecula suffices to give to it, or remove from it, the property of combining with iodine, its nature remaining the same. (Biot, *Journ. Pharm.*, v. 1844, p. 445.)

II.

References on the Subject of the Rotatory Polarization of Light.

Biot, in his paper *Sur la Construction des Appareils destinés à observer le Pouvoir rotatoire des Liquides*, published in the *Annales de Chimie et de Physique*, t. lxxiv. p. 401., makes the following references to his papers on rotatory phenomena and their application to chemistry :—

1. *Mém. de l'Académie des Sciences,* t. ii., 1817 (rotations of certain substances).
2. *Ditto,* t. xiii. p. 39., 1812 (application to organic chemistry).
3. *Ditto,* t. xiii. p. 437. (fecula and gum).
4. *Ditto,* t. xv. p. 93. (tartaric acid, alcohol, wood spirit).
5. *Ditto,* t. xvi. p. 229. (fundamental points of chemical mechanics).
6. *Nouv. Ann. du Mus.,* t. iii. p. 47. (vegetation of grasses).
7. *Comptes Rendus,* 6 Juin, 1836, t. ii. (disposition of rotatory substances, &c.).

III.

References on the Subject of the Turpentines.

Mém. de l'Acad. des Sciences (read Sept. 22, 1818), t. ii. p. 46. (for 1817, but published in 1819). Biot mentions here how he accidentally discovered the rotation of oil of turpentine, when examining crystallized plates placed in very refracting media, such as this oil. He perceived that this liquid modified the condition of the polarized rays which traversed it. But he observes, that while in rock crystal there are two opposite directions of rotation, in turpentine the rotation is always from the right towards the left of the observer.

In this paper he also mentions other liquids which also possess rotatory phenomena; some of them in an opposite direction, that is, from the left to the right (pp. 46, and 47.).

The mean rotation of the rays transmitted by red glass was, for every centimètre, 2°·7057 (p. 92.) at 20° centigrade. This is for the turpentine of commerce (pp. 92, and 93.).

For the same rays transmitted through turpentine purified by several distillations the rotation for every centimètre was 2°·8628 at the temperature of + 3° centigrade (pp. 92, and 93.).

By mixing essence of lemons with essence of turpentine the rotations are compensated:

I. Essence of Lemon.—Rotation left to right ↗. The principal section of the prism being in the direction of primitive polarization, the *ordinary ray* is sombre red; the *extraordinary ray* greenish yellow. By interposing the red glass and turning the prism 66° ↗, the extraordinary ray vanishes.

II. Essence of Turpentine.—Rotation right to left. ↖. When the principal section of the prism corresponds with primitive polarization, the *ordinary ray* is orange; the *extraordinary ray* bluish white. By interposing red glass and turning it 38°, to the left ↖, the *extraordinary ray* becomes nothing.

The above statements apply to a length of fluid$=151^{\mathrm{mm}}\cdot5$.

Hence the rotatory force of essence of lemons is to that of turpentine as 66 : 38. Consequently, if we mix 66 parts of the second (that is, the oil of turpentine) with 38 parts of the first (that is, of the oil of lemons), we have a mixture in the proportion of their reciprocal intensities, and in which the powers of rotation will be compensated (p. 118.).

Biot then describes the rotatory power of the vapour of turpentine (p. 125.).

In the *Mémoires de l'Académie*, t. xiii., 1835, is a memoir by Biot (read 5th November 1832), entitled *Mémoire sur la Polarisation circulaire et sur ses Applications à la Chimie organique.* In this he gives the deviations of the oils, &c., which I have copied in the printed table at p. 272. of my Lectures on Polarized Light.

The oil of turpentine which he examined had been rectified with the greatest care by M. Dumas, and was the same of which he published an analysis in the *Annales de Chimie et de Physique* for July 1832. The oil he describes as being limpid and a little greenish. The temperature is not stated.

Mitscherlich, On the Circular Polarization Apparatus for Saccharine Liquids, in *Central Blatt*, 1851.

English Oil of Turpentine, examined by Bourchardat, May 21. 1845: —

Temperature = 15° centigrade.
Rotation, right-handed = 22°·5.
„ „ „ with red glass = 17°.
„ „ „ „ „ 16°·9.
Length of tube used = 108 millimètres.

The sp. gr., according to Guibourt, was 79°; Gay Lussac, at 12° centigrade.

Essential Oil of the Silver Fir, Abies taxifolia (Abies picea) :—

Sp. gr., according to Guibourt, was 81°; Gay Lussac, at 12° centigrade.

Temperature = 15° centigrade.

Rotation, left-handed = 26°·25 (for the flax-flower tint).

„ „ red glass = 19°.

Length of tube used, 199·4 millimètres.

Now, as 199·4 : 1000 :: 26·25 : 13·2; so that the rotation would be 13°·2 for a tube of 100 millimètres in length.

J. P's rule :—

1. To reduce the rotation *without* red glass to that with, multiply by 23 and divide by 30.

   Ex. $\frac{22^{\circ}\cdot 5 \times 23}{30} = 17\cdot 25.$

2. To reduce the *rotation with* to that without red glass, multiply by 30 and divide by 23.

   Ex. $\frac{17 \times 30}{23} = 22\cdot 2.$

IV.

Extracts from Biot's Memoir (Ann. Chém. Phys., *vol. lxxiv.,* 1840), *quoted above.*

Zero point, direct polarization 0°, is when *E* (extraordinary image) is entirely or almost completely insensible.

If water, spirit, or other inactive liquids be introduced, *E* remains invisible.

If oil of turpentine, tartaric acid solution, &c., &c., be interposed, *E* reappears. The primitive polarization is disturbed.

If red glass (coloured by protoxide of copper) be interposed, and the analyzer turned right or left, the image *E* again disappears. The arc traversed by the *alidade*, from the zero point, measures the angle of deviation which the plane of polarization of the red rays suffers.

But the deviations of the different simple rays are almost exactly reciprocal to the squares of the lengths of the undulations in the wave theory. Tartaric acid is an exception to this. Hence, in the succession of the extraordinary tints, which appear as the prism is rotated, there is one extremely distinct and easily recognizable, which responds with a singular approximation to the deviation of the pure yellow rays, and which we reduce to that of the rays transmitted by the red glass, by multiplying it by $\frac{23}{30}$. This tint is a bluish violet, which immediately follows the intense blue, and immediately precedes the yellowish red, in the progress of the rotation; and both, by its special nature and by its striking opposition with the two other [tints], between which it is always comprised, it is impossible not to recognize, when we have once sought for it.

Observation thus effected is more easy and prompt than with red glass, and the appearance and change of colour very sensible.

V.

Tartaric Acid.

Biot, in his *Mémoire sur la Polarization circulaire* (read to the Academy of Sciences on the 5th November, 1832, and published in the 13th volume of the *Mémoires*, 1835), says, at p. 138., that there are entire classes of organic compounds which, if not actually without the power of circular polarization, at least possess it in a degree which relatively is very feeble.

But in the Table G, p. 168. of the same memoir, he has the following: —

"Crystallized tartaric acid dissolved in water, in the proportion of $53^{g}{\cdot}607$ of acid to $52^{g}{\cdot}230$ of water.—160 millimètres of tube. Solution colourless. Rotation + $8^{\circ}{\cdot}5$ ↗, strongest on the least refrangible rays."

The most complete account of the polarizing powers of solutions of tartaric acid are given by Biot in his *Méthodes mathématiques et experimentales pour discerner les Mélanges et les Combinaisons chimiques définies ou non définies, qui agissent sur la Lumière polarisée; suivies d'applications aux combinaisons de l'acide tartrique avec l'eau, l'alcohol et l'esprit de bois,*" presented to the Academy on the 11th of January, 1836, and published in 15th volume of the *Mémoires.* The following are extracts: —

The tartaric acid used was of English manufacture (p. 144.).

"In all active bodies the rotatory power exercised on the different simple rays is unequal. In all, with the single exception at present known of tartaric acid, this inequality follows one same law, rendered evident by the identity of compound colours, which appear when we analyze white polarized light, transmitted in all these systems through thicknesses inverse of their power. The exception presented in this respect by tartaric acid is the more remarkable, since all its combinations with salifiable bases, even with boracic acid, have rotatory powers conformable to the general law; at least, within the limits of precision which I am able to attain by composing the series of their tints with those which produce all the other bodies."

VI.

" *Formula for determining the absolute Weight of pure Diabetic Sugar contained in a litre* (= 1·7608 *imperial pints*) *of Diabetic Urine.* (Given me by Bourchardat, 1845.)

" According to the experiments of M. Biot on pure diabetic sugar, if we examine diabetic urine in a tube whose entire length in millimètres is = L, and the deviation measured by the naked eye, for the extraordinary violaceous blue tint which immediately precedes the yellowish red, be a, the absolute weight of sugar contained in a litre of this urine will be, in grammes, 2353, 6 a (with the orange yellow tube $2340 . \frac{a}{L}$).

" If the length of the tube is less than 350 millimètres, and the blue and yellowish red colours be very apparent, on account of the slight colour of the liquor, this evaluation will be rather in excess than too little. If, on the contrary, L surpasses 350 millimètres, or if the urine is so strongly coloured that the colours differ but little before and after the point of the passage, the evaluation will be rather too low than too high.

"In every case the uncertainty is of very little importance, especially for diagnosis. It proceeds from the difference which the more or less intense colour produces in the determination of the point of passage where we measure the deviation when we observe it by the naked eye. We cause it to disappear by always observing it through red glass. This renders the deviations comparable with each other, but this will here render the observations much more troublesome without any real utility.

"Here are two examples, which show the application of the formula:—

"1. We have a diabetic urine in a tube whose total length L was 500 millimètres, and we have found a deviation a equal to 15°; by multiplying at first 2353·6 by 15, we have for a product 35304·0, which, being divided by 500, gives for the quotient 70·608. This is the weight of diabetic sugar contained in each litre of the urine examined; and the evaluation is rather too low than too high.

"2. The tube of observation had for its length 347 millimètres; the deviation observed a was 10°·967. The urine was very coloured through this thickness.

"By multiplying 2353·6 by 10°·967, we have, 24870·5 for a product, neglecting, *after the multiplication*, the decimals beyond the tenths. Now this number 24870·5, being divided by 347, gives for the quotient 71·673. This is the weight of diabetic sugar contained in each litre of this urine; and the evaluation is rather below than above, because the urine will appear very coloured in the observation tube.

"These calculations of multiplication and of division are made in a moment by a table of logarithms.

"When the urine is very coloured, the extraordinary image remains insensible to the eye during a certain amplitude of course of the doubly refracting prism. We determine, then, the limits of its disappearance and of its reappearance by a certain number of successive observations. The arithmetical mean between the extremes is the true measure of a. It is thus that, in the second example, we have obtained the fractions of the degree of deviation."

L = length of tube.
a = deviation.
2353·6, an empirical number.

Let $L = 303$ millimètres,
$a = 40°$;

$$\text{Then } \frac{2353{\cdot}6 \times a}{L} = 310{\cdot}70 \left\{ \begin{array}{l} \text{weight of diabetic} \\ \quad \text{sugar.} \end{array} \right.$$

l = length of tube in English inches and fractions,
a = deviation of the ray.
812·20607, an empirical number.

$$\frac{812{\cdot}20607 \times a}{l} = \left\{ \begin{array}{l} \text{English troy grains of sugar in} \\ \quad \text{one imperial pint of diabetic} \\ \quad \text{urine.} \end{array} \right.$$

VII.

On Fraunhofer's Spectra.

[It has been stated above generally, in respect to the colours produced by interference, that they are always *compound* tints, and in no case *pure* prismatic colours. To this there is, however, one remarkable exception,—an exception which, nevertheless, is fully accounted for by the theory of interferences. It occurs in the following experiment, in many ways an important and interesting one.

Make a small frame to fit on to and surround the object end of a telescope. Across this frame stretch a great number of fine threads close together, so as to form a fine grating of parallel lines, covering the object glass : fine sewing cotton-thread answers well. Now direct the telescope to a distant narrow slit in a screen or window-shutter through which the light of the sky passes, taking care that the threads are parallel to the slit. On looking through the telescope, the white image of the slit will be seen in the centre, accompanied on each side by a perfectly pure spectrum of the prismatic colours in the usual order, the violet being nearest the centre. So pure are these spectra that Fraunhofer, with his excellent glasses, was able to distinguish the dark lines in them (see p. 35.): with moderate telescopes it is probably impossible to see these. Beyond these other spectra may be seen, but in which the colours are more and more superposed and compound. They are called *Fraunhofer's Spectra*, from their discoverer, who also explained them by the interference theory, though the investigation is too long to insert here.] *

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* The student is referred for full details to Professor Powell's *Elementary Treatise on Experimental Optics*, p. 151; and to Mr. Airy's Tracts, *Undulation Theory*, Art. 83.

NOTES

OF A

LECTURE ON THE MICROSCOPE.

INTRODUCTION.

THE object of this Lecture is to draw the especial attention of members, associates, and students of this society to some few of the pharmacological revelations of the Microscope, and thereby to promote the more frequent employment of this agent, which, to the pharmaceutist, I hold to be one of his most important, valuable, instructive, and useful scientific instruments.

This Lecture is intended to be of the most elementary character, being essentially adapted for the uninitiated. I feel it necessary to premise this statement as an apology to those who are familiar with the structure and uses of the microscope, and who might, perhaps, be led to expect that I was about to treat the subject in a different, and to them more instructive manner.

Since the Lecture was announced I have had communications with some of the persons who, I presume, are here present, requesting me to furnish them, through this medium, with information and details, which certainly I had no intention of doing, on account of the invidious position I should place myself in.

I had proposed to excite the desire of pharmaceutists for microscopical investigations. But I find the appetite pre-exists; and they are anxious to know where, how, and at what cost they can gratify it. I have been asked what microscope maker I recommend; what magnifying power is required; and what is the cost of a proper instrument for the pharmaceutist?

These inquiries have induced me to devote a portion of this Lecture to a few details illustrative of the structure of the microscope, and will show how difficult it is to answer these questions.

The fact is that, when we talk about a microscope, we do not speak of an instrument of definite extent, or consisting of a constant and unvarying number of parts. There are certain essential parts, and many others non-essential or optional. Yet some of these non-essentials are, notwithstanding, so useful, that microscopical investigations can scarcely be carried on without them.

ON THE MICROSCOPE IN GENERAL.

We derive the term *microscope* from μικρός *little*, and σκοπέω *I view*. It may be defined as,—

1. An instrument which enables us to *view* objects which are too *little* to be seen by the naked eye.

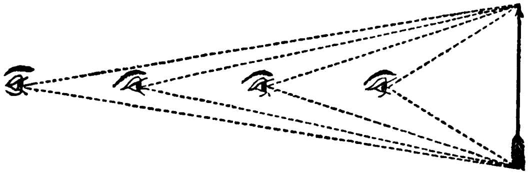
2. An instrument which enables us to see objects distinctly at a shorter distance from the eye than is compatible with distinct vision.

3. An instrument which enlarges the angle of vision (or optical angle), and thereby enables us to see objects too minute to be seen at the distance of distinct vision.

4. An instrument to enlarge and render distinct the image of near objects.

At different distances from the eye the same object subtends different angles, as may be illustrated by the annexed diagram, which needs no explanation.

Fig. 97.



The nearer we approach a body the greater the angle, and, therefore, the larger the body appears.

If we look at a pin or needle through a pinhole aperture in a card, the nearer the pin or needle is to the eye the larger is the apparent magnitude of the body. For the power of adjustment for distances, see explanation in Muller, p. 1153. For distinct vision the rays must be brought to a perfect focus at the retina. The eye can adapt itself so as to produce this effect within certain distances. This power of adaptation varies in different individuals. From 5 to 10 inches is the distance of distinct vision.

If a small object be brought very near to the eye, it appears very large, but is wholly indistinct, because the humours of the eye are not sufficiently refractive to cause the rays to meet on the retina: they, therefore, converge behind the retina. Though the object looks larger, it is seen with indistinctness, and therefore no advantage is gained. Thus, with respect to these small bodies, all men may be said to be long-sighted: they require glasses of a convex nature to make the bodies visible.

A microscope here proves serviceable. An artificial image is here formed in front of the eye. The rays meeting to form this image not being received there by any opaque surface, diverge again from this point in the same way as if the object for which they originally radiated were there situated.

Thus it gives the eye the advantage of the augmented magnitude, and removes the inconvenience that arises from the too great proximity of the object. The picture formed upon the retina corresponds with one of an object greatly increased in its dimensions and viewed at the smallest ordinary distance of distinct vision.

Microscopes are of two kinds:—

1. *Simple.*
2. *Compound.*

1. The *simple microscope* consists of a single convex lens with a very short focal distance, which may be called a simple magnifier. Or, again, the *simple* microscope might be formed of several lenses; but then these must be combined so as to form a *compound lens* whose function is to produce an effect on the rays equivalent to a single lens.

2. The *compound* microscope consists of a combination either of lenses or of a speculum with lenses. In the first case it is called a *dioptric* or *refracting* microscope; in the latter a *catoptric* or *reflecting* microscope.

The compound microscopes in general use are of the dioptric or refracting kind.

Refracting Compound Microscopes.

These consist of at least two convex lenses: one nearest to the object and therefore called the *object-glass,* the other nearest to the eye, and therefore termed the *eye-glass.*

By this a *double magnification* takes place: the object-glass produces an enlarged real image of the object, and the eye-glass magnifies this image in the same way as a simple microscope does the object.

Hence, then, with the *same object-glass* different degrees of magnification may be obtained by using *eye-glasses* of different powers.

It is curious, however, that if, from some imperfection in the object-glass, it gives a distorted or imperfect image, the eye-glass will magnify the distortion or imperfection. Hence it is not desirable to use too much magnifying power in the eye-glass, especially for the high powers of object-glasses of short foci. At least, it is necessary, in the first instance, to know what the goodness of the object-glass is, in order to determine what powers it will bear.

The chief qualities which a microscope ought to possess may be distinguished as,—

1. *Penetrativeness,* (called by Quekett *power of definition,*) which is principally effected by the *angle of aperture.*

2. *Definitiveness,* (called by Quekett *correctness of definition,*) depends on the *balance of the aberrations* and the *workmanship.*

The quantity of light collected and transmitted by each lens will be as the squares of their diameters.

Increase of illumination cannot compensate for deficiency of aperture. It cannot be made to increase the *relative proportions* of light which proceed from these minute parts.

IMPERFECTION OF MICROSCOPES, AND MEANS OF CORRECTION.

The causes of imperfection which give rise to want of *defining power* and want of *penetrative power*, or want of *definitiveness* and *penetrativeness*, are chiefly the following: —

1. *Spherical aberration.*

   The means of correction are,—

   a. *Stops* or *perforated diaphragms*, to limit the area of the rays.

   β. *Aplanatic glasses* (*ἀπλανητικός not disposed to wander* or *roam*).

   γ. *Augmentation of density* or *refractive power in the centre of lens*, or in the crystalline lens of the eye; but this property cannot be applied artificially.

2. *Chromatic aberration* or *dispersion.*

   The means of corrections are,—

   Achromatic glasses (*ἀχρωματικός devoid of colour*).

   These are made of lenses composed of

glasses of different refractive and dispersive power, namely, *flint* and *plate* glass.

Corrections for aberration remedy some defects of *defining power.*

3. *Deficiency of light,* or *small aperture.*

The larger the angle of aperture, the greater the power of *penetration.*

Contracting the aperture of the object glass lessens the aberrations.

The higher the magnifying power the greater the aberrations.

Twenty years ago it was thought a great achievement to make an achromatic object-glass which should transmit a pencil of an angle of about 20°. They are now made to transmit more than 90°. Mr. Ross's $\frac{1}{12}$th transmits a pencil of 120°. He has made one which transmitted a pencil of 135°, the largest angular pencil that can be passed through a microscopic object-glass.

4. *Errors in the centring and adjusting of lenses.*

Supposing that the glasses are worked with great accuracy, the lenses require to be most accurately centred and adjusted. Mr. Beck informs me that the grinding, centring, and adjusting of the lenses composing a $\frac{1}{8}$th object-glass is a good week's work.

5. *Bad quality of glass.*
6. *Tremor* or *movement.*

   This depends on the stand.

7. *Inconvenience* of movement.

The modern improvements introduced into the construction of achromatic glasses for the microscope are chiefly due to the discoveries of Mr. Lister, who found that, by using for his powers combinations of two or more, separated by determined intervals, much larger pencils could be brought to accurate foci, and the instrument would bear with distinctness much higher magnifying powers than with a single achromatic object-glass.

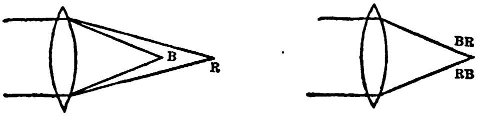
He also introduced the practice of joining together the glasses composing the doublets or triplets by Canada balsam.

Mr. Ross applied Mr. Lister's principles with such success, that he obtained achromatic object glasses so accurately corrected, that even the thickness of the glass or mica used to cover the object disturbed the correction. To remedy this, he contrived a method of compensation. By means of a screw-collar he managed to vary the distance between the first and second compound lens, according as the object is uncovered or covered, and according to the thickness of the cover.

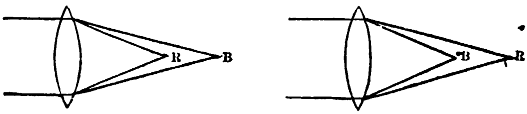
In Mr. Ross's article on the Microscope in the *Penny Cyclopædia*, the objectives of the high powers are said to be three *doublets*. *Two doublets* and one *triplet* is now used. I am informed that this improvement is due to Mr. Lister. I have not seen any notice of the use of this triplet in any works on the microscope which I have met with.

Eye-piece. This is not achromatic. The slightest inspection of it will show this. Here, then, you will say is a great defect. Great expense and trouble is lavished on the object-glasses, and by them a colourless beam of light is obtained: but when this reaches the eye-piece it is dispersed and coloured. Such, however, is not the case. The dispersion of the eye-piece is counteracted by the *over-correction* of the object-glass.

Fig. 98.



Uncorrected Object-glass. *Achromatic Object.*



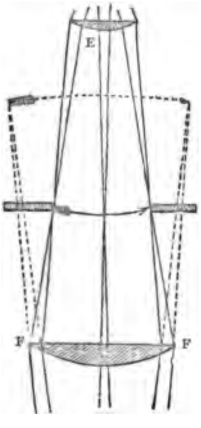
Over-corrected Object-glass. *Un-corrected Eye-piece.*

B signifies *blue* rays.
R " *red* "

PRESENT STRUCTURE OF THE COMPOUND MICROSCOPE.

1. The *Object-glasses* are achromatic, as already described.
2. *Eye-piece.* The one in use is that called the Huyghenian. It consists of two plano-convex lenses of *plate glass*: the lower and larger lens is called the *field-glass*; the upper and smaller one the *eye-glass*, or the *magnifier.*

Fig. 99.
Huyghenian Eye-piece.



For the details of the Huyghenian eye-piece and its compensating property, the student is referred to the *Penny Cyclopædia*, Art. Microscope, p. 186., from which this figure is taken.

Three *eye-pieces* are made, called A, B, and C, or 1, 2, and 3. They are of different degrees of power: the higher the power, the greater the convexity of the lenses and the nearer they are placed together.

The magnifying power of the eye-pieces made by different makers is not absolutely alike.

Good microscope observers object to the use of very powerful eye-pieces, especially for object-glasses of high power.

3. *Draw-tube.* By drawing out the tube we increase the distance of the object-glass from the eye-piece, and thereby increase the size of the image. Within certain limits this may be usefully employed. It requires the object to be brought nearer the power; and, as the rays then fall more obliquely on the object-glass, the errors of aberration are increased.

Fig. 100.

Object-Glasses, or Powers.

$\frac{1}{8}$, $\frac{1}{4}$ *and* $\frac{4}{10}$*-inch focus.*

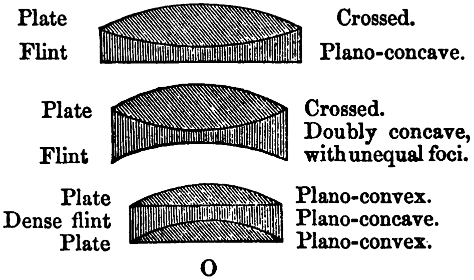


Fig. 101.

$\frac{2}{3}$ *and* 2*-inch focus.*

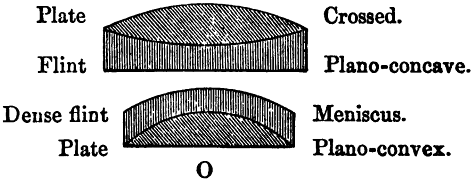
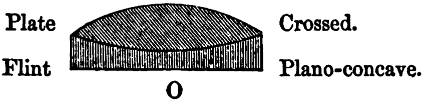


Fig. 102.
3-*inch focus.*



ACTION OF THE MICROSCOPE.

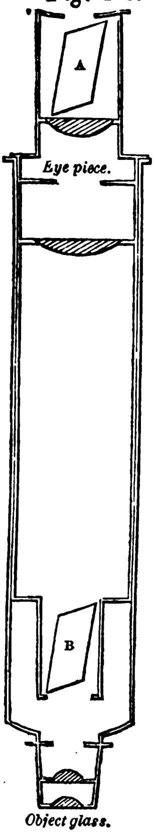
1. The *Object-glasses* refract the rays coming from the object, and would bring them to a focus.
2. The *Field-glass* changes the course of the rays in such a manner that the image may be formed of dimensions not too great to come within the range of the eye-piece, and, consequently, to allow more of the object to be seen at once. It also serves to correct the errors of the eye-glass.
3. *Eye-glass.* The whole of the image produced by the field-glass is within the range of vision of the eye-glass.

POLARIZING MICROSCOPE.

In applying the compound microscope to observe the phenomena of polarization there are two situations in which both the polarizer and analyzer may be placed. The former may be placed in the opening of the stage, immediately below the object, or (which is preferable, when a high power is used) at the bottom of the achromatic condenser.

The analyzer may be placed in a cap above the eye-piece (marked A in the diagram), or at the bottom of the draw-tube (marked B); and each has its peculiar advantages. When placed at A, it can only be used with the lowest eye-piece; and even then slightly diminishes the field of vision; but it is easily rotated, and does but little injury to the definition. When at B, it may be used with any eye-piece, and does not diminish the field; but it cannot be rotated so easily, and it materially deteriorates the definition. For the latter reason I have placed mine above the eye-piece in the situation marked A.

Fig. 103.



Body of the compound microscope, showing the two situations in which the analyzer may be placed.

Dr. Leeson tells me that a plate of pale tourmaline at B answers extremely well, as it has the advantage of not interfering with the extent of field, and, being thin, has but little effect on the definition compared with the thick prism.

PURCHASE AND PRICES OF MICROSCOPES.

Advice.

1. Buy of a good maker.
2. The first thing to buy is the stand.
3. Then,

			STUDENT'S.	
	1.	2.	3. With stage movements.	4.
One power ...... $\frac{1}{4}$ power	£16 16 0 5 5 0	£12 12 0 5 5 0	£9 9 0 5 5 0	£5 10 0 5 5 0
	£22 1 0 2 eye-pieces. &c.	£17 17 0	£14 14 0 Box.	£10 15 0 Box.

Stage £4 4 0

	£	s.	d.
Or	5	10	0
$\frac{2}{3}$-inch...............	3	3	0
	£8	13	0

Cautions. — Continental (French) object-glasses are much cheaper. The *objectives* are sold in sets, of which 1, 2, or 3 may be used at once; by which great variety of power is gained, but perfection is sacrificed. No single objective can be thoroughly corrected; each combination to be corrected for itself alone: hence English achromatic combinations consist of two or three compound lenses which cannot be separated.

A high magnifying power is not necessarily good. I saw, in Leadenhall-street, a microscope marked one guinea, said to magnify 1000 times.

Time required for centring and adjusting.

PRICES OF MICROSCOPES EXCLUSIVE OF OBJECT-GLASSES.

	£	s.	d.
1. Best microscope, on double pillar, and sconces. Body with quick and slow motions, graduated sliding tube, and two corrected Huyghenian eye-pieces; stages with vertical and horizontal rackwork actions (given by rackwork and screw or lever); sliding and revolving plane and spring clamping piece; revolving diaphragm; large double mirror; forceps and joint; pliers and glass plates; with thin glass, &c.	16	16	0
Best Spanish mahogany case, with box and drawers	3	10	0
Or Honduras ditto, with box	2	6	0
2. Best smaller microscope, on single pillar and joints, with actions same as the above, &c.	12	12	0
Flat mahogany case for ditto, with drawer	1	16	0
3. Student's microscope, with uprights and joints, actions same as the above; one eye-piece, concave mirror, and others; actions same as the above; mahogany case included	9	9	0
4. The above with plain stage; consisting of sliding piece and clamping spring, one eye-piece, concave mirror, and others; actions same as the above	5	10	0
5. Plain microscope, for hospital use, with quick and slow motions to body, one eye-piece, and case	2	15	0

APPARATUS EXTRA.

	£	s.	d.
Eye-pieces ....from 13*s.* to	0	17	6
Bull's-eye lens, or illuminator, on stand....	1	1	0
Ditto smaller..................................	0	12	0
Side illuminator, with universal joint.......	0	18	0
Side silver reflector, with joints.............	1	1	0
Erecting glasses................................	1	0	0
Three dark wells and fittings..................	0	12	6
One ditto for small microscope	0	6	0
Brasswork of achromatic condenser........	1	10	0
" " for student's microscope..	0	7	6
Set of lenses for ditto..............	1	10	0
Camera lucida....................................	1	0	0
Micrometer for stage............ from 5*s.* to	0	10	0
" to eye-piece.......................	1	0	0
Live boxes .... from 6*s.* 6*d.* to	0	14	0
Compressorium..................................	1	1	0
Glass troughs................ from 3*s.* 6*d.* to	0	8	6
Polarizing apparatus	2	10	0

PRICES OF OBJECT-GLASSES.

Object-glasses.	£	s.	d.	Lieberkuhn's additional. £	s.	d.
3 and 1½-inch combination.......	4	0	0	0	15	0
1½-inch.........................	3	0	0			
1¼ and ⅔ "	4	4	0	0	11	0
⅔ "	3	3	0			
4/10 without cone............	4	4	0	0	10	0
4/10 with "	5	5	0			
¼-inch	5	5	0	0	6	0
⅛ "	7	7	0			

	£	s.	d.
Student's Microscope, with quick and slow motions to body; sliding tube, and one corrected Huyghenian eye-piece, sliding plane, and spring clamping piece to stage; forceps; &c.; and packed in mahogany case	5	10	0
2nd eye-piece....................................	0	15	0
$\frac{4}{10}$-inch object-glasses without cone..........	6	4	0
	£10	9	0

[These details seem to have been required for the information of those to whom Dr. Pereira's Lecture was addressed; they are therefore here retained, though the reader should be aware that such particulars can hardly be considered as universally applicable, and that various changes in the arrangements and prices are continually occurring.]

THE END.

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